Conserving Groundwater Supply in the Arkansas Delta using On-Farm Reservoirs

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Abstract: We model water use, aquifer recharge and producer returns over 30 years in three watersheds to determine impact of modified water cost and construction of reservoirs. To maintain groundwater resources, raising cost of pumped water by a buffer value to the aquifer resource and using surface storage looked most promising.

Keywords: Groundwater, Reservoirs, Farms

Introduction

Groundwater is 73% of the total water used in the Arkansas Delta crop production region, and the state is the fourth largest user of groundwater in the nation (ASWCC 2004; Schaible and Aillery 2010). Agriculture depends on water for the irrigation of standing crops and the application of fertilizers and pesticides. Water is also utilized as a physical herbicide in rice production, minimizing chemical application (Bouldin et al. 2004). In 2007, the state supported 4.5 million acres of crop production under irrigation, including water demanding crops such as rice and corn, and irrigated acres in the Delta have increased strongly ever since the early 1980s (Schaible and Aillery 2010). The east-central area of the state is experiencing a depletion of the Alluvial aquifer that is unsustainable if pumping is not curtailed and no recharge mechanism for the groundwater is created (ANRC 2012). This puts water-intensive agricultural production at risk in the future in addition to the adverse effects of land subsidence, saline water encroachment, increased cost to well users, and reduced base flow to streams and wetlands.

As a result, state officials and policy makers are calling for conservation methods by the agricultural community and for legislation encouraging alternate plans for water utilization. Irrigation water can be recaptured following release from flooded fields and redirected to reservoirs for future reuse. Rainfall runoff from a surrounding watershed can be stored for subsequent use in reservoirs. Water in these systems is then utilized numerous times throughout a growing season with surplus collected during rainfall events. Conservation of the water and the concurrent capture of runoff are beneficial to both agriculture and the natural ecosystem.

This study evaluates net returns from agricultural production, crop choice, and water use through the construction of on-farm reservoirs across the Arkansas Delta. The study area encompasses three eight-digit hydrological unit code (HUC) watersheds (Figure 1) that span the farming region of the Delta where water use is the least sustainable. We model the spatial pattern of groundwater flow in the presence of pumping as cones of depression within the aquifer. Reservoirs to mitigate unsustainable groundwater use and surface water pollution can receive water from rainfall, diverted surface water, and reused irrigation water from agricultural fields otherwise targeted for discharge into receiving streams. A model optimizing farm net returns over a 30-year period spatially determines the allocation of acreage to crops and reservoir sites subject to constraints on the supply of groundwater, reservoir water if reservoirs are built, and the chosen crop mix. Groundwater and reservoir water use in addition to the saturated thickness of the aquifer are tracked over time in response to crop allocation and the reservoir construction decisions farmers make.

In earlier work, Popp et al. (2010) examine the response of farmer's crop allocation decisions to irrigation restrictions and a hypothetical market for bioenergy crops in the Arkansas Delta. They find that introducing alternative energy crops would both reduce groundwater use and stabilize producer returns, albeit with significant spatial income redistribution to crop production throughout the state. Other studies have focused on helping individual farmers to decide whether to build on-farm reservoirs. The Modified Arkansas Off-stream Reservoir Analysis (MARORA) decision support software estimates optimal reservoir sizes on a farm for different rice producing locations with different saturated thickness levels and groundwater decline rates (Hristovska et al. 2010). Results indicate the thickness of the aquifer needs to be as low as 30 feet before a reservoir is needed, and the optimal size depends on the farm's productivity and groundwater decline rate. Popp et al. (2003) combine MARORA with the erosion productivity impact calculator to evaluate how on-farm reservoirs affect farm productivity and sediment control. Results indicate reservoirs can simultaneously improve profitability and reduce pollutant run-off.

Society is often not aware of the non-market values from conservation until the non-market services are in jeopardy (Cairns 1997). Bouldin et al. (2004) has incorporated non-market values such as top-soil conservation and nutrient retention in a cost-benefit analysis of on-farm reservoirs for agricultural systems utilizing a reservoir-ditch-relift system for crop irrigation. Tsur and Graham-Tomasi (1990) investigate the buffer value of groundwater, the ability to mitigate undesired fluctuations in the supply of surface water, in a stochastic-dynamic optimization problem. They find the buffer value of groundwater can comprise up to 84% of the total value of groundwater in cases with highly variable surface water, a small aquifer, and high unit pumping costs. Our model of farm production with reservoirs is reevaluated using an objective that includes the buffer value of groundwater to compare to earlier results of the water supply conditions.

The primary objective of this paper are thus to develop estimates of ground water level changes over 30 years for three watersheds when i) irrigation water costs are modified from direct costs associated with pumping water from variable depths by adding a buffer value to the aquifer resource and ii) modeling the impact of reservoir construction (including tracking of groundwater recharge from these reservoirs) in comparison to continued reliance on ground water alone. Crop yields, weather, cost of production and crop commodity prices are held constant for this analysis.

Methods

Dynamics of land and water use

Here we model the spatial-dynamics of land and water use in the rice-soybean production region of the Delta focusing on the supply of water available in the underlying aquifer. Our model follows from a map grid representation of spatially symmetric cones of depression from groundwater pumping. The model consists of a grid of m cells (sites) and accounts for the amount of available groundwater by time period based on the pumping decisions of farms in and around the cell weighted by distance.

We track the cumulative amount of land in use j for n land types (corn, cotton, rice, irrigated soybean and non-irrigated soybean) at the end of period t with $L_{ij}(t)$. We assume land (in acres) can be converted to on-farm reservoirs $FR_{ij}(t)$ from an existing land use j during period t, and the cumulative amount of land converted to reservoirs at the end of period t is $R_i(t)$. Farmers can choose to switch land out of water-intensive rice into irrigated soybeans in response to a growing water shortage, and this is tracked with the variable $RS_i(t)$. The constraint on groundwater availability may lead farmers to switch land out of irrigated crops into non-irrigated soybean, and the variable tracking the land switching to non-irrigated soybean is $DS_i(t)$. Using these definitions, we model the dynamics of land use in each site as a system of difference equations:

$$\begin{aligned}
L_{ij}(t) &= L_{ij}(t-1) - FR_{ij}(t) - DS_{ij}(t) - RS_i(t), \text{ for } j = \text{rice} \\
L_{ij}(t) &= L_{ij}(t-1) - FR_{ij}(t) - DS_{ij}(t) + RS_i(t), \text{ for } j = \text{irr. soybean} \\
L_{ij}(t) &= L_{ij}(t-1) - FR_{ij}(t) + \textstyle\sum_{j=1}^{n} DS_{ij}(t), \text{ for } j = \text{non-irr. soybean} \\
L_{ij}(t) &= L_{ij}(t-1) - FR_{ij}(t) - DS_{ij}(t), \text{ for all } j \neq \text{rice, irr. soybean, non-irr. soybean}
\end{aligned} \tag{1}$$

$$R_i(t) = R_i(t-1) + \textstyle\sum_{j=1}^{n} FR_{ij}(t) \tag{2}$$

Each period, the amount of land in use j is reduced by the amount of land converted to on-farm reservoirs or switched into non-irrigated soybean production. For cropland in rice, a switch to irrigated soybean can also occur where the decline in rice is exactly offset by the increase in irrigated soybean. The cumulative amount of land in non-irrigated soybean by the end of period t is the amount of land in non-irrigated soybean in earlier periods and the sum of the amount of land added to non-irrigated soybean from all land uses j less the land converted to on-farm reservoirs during period t (Eq. 1). The cumulative amount of land in on-farm reservoirs by the end of period t is the amount of land in reservoirs in earlier periods and the sum of the amount of land added to reservoirs from all land uses j during period t (Eq. 2). The total amount of land converted to a reservoir from land use j must be less than the amount of land in use j as of period t: $\sum_t FR_{ij}(t) \leq L_{ij}(t)$

Let $AQ_i(t)$ be the amount of groundwater (acre-feet) stored in the aquifer beneath site i at the end of the period t. The amount of water pumped from the ground is $GW_i(t)$ during period t, and the amount of water pumped from the on-farm reservoirs is $RW_i(t)$. The acre-feet of water that a one acre reservoir can hold in a period is ω. The reservoirs allow some of the water to infiltrate through the soil and recharge the aquifer. The amount of water that a full reservoir, an acre in size, can recharge the aquifer is r_i, which depends on the soil type present at site i. Water pumped from the reservoir reduces the amount of water available to infiltrate down to the aquifer. The proportional reduction of recharge is modeled linearly as $\left(1 - \frac{RW_i(t)}{\omega R_i(t)}\right)$. Crops differ in their requirements for the amount water in a period, and the demand for water by land type j for irrigation is given by wd_j.

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 exponential function of the distance 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 a foot using a pump, c^p, and the initial depth to the groundwater within aquifer, dp_i. The dynamics of water use and pumping cost at each site is then represented by:

$$\sum_{j=1}^{n} wd_j L_{ij}(t) \le GW_i(t) + RW_i(t) \tag{3}$$

$$RW_i(t) \le \omega R_i(t) \tag{4}$$

$$AQ_i(t) = AQ_i(t-1) + r_i R_i(t)\left(1 - \frac{RW_i(t)}{\omega R_i(t)}\right) - \sum_{k=1}^{m} p_{ik} GW_k(t) \tag{5}$$

$$GC_i(t) = c^p \left(dp_i + \frac{\left(AQ_i(0) - AQ_i(t)\right)}{\sum_{j=1}^{n} L_{ij}(t)} \right) \tag{6}$$

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 by the reservoirs less the amount of water pumped from surrounding sites weighted by the proximity to site i (Eq. 5). Pumping costs of groundwater to the surface depend on the depth to the aquifer according to the depletion of the aquifer from earlier pumping multiplied by the cost per foot of lifting an acre-foot of water.

Farm net benefits objective

We assume a planner determines the optimal construction of on-farm reservoirs subject to land and water use constraints and assumptions about the management of the crops grown on the private farm. The planner's objective is to maximize the net benefits of farm production less the management costs of reservoir construction and use. Several economic parameters are needed to complete the formulation. The price per unit of the crop is pr_j and the cost to produce an acre of the crop is ca_j, which depend on the crop j. The yield of crop j per acre is y_{ij} at site i. The net value per acre for crop j is then $pr_j y_j - ca_j$ excluding water pumping and potential reservoir construction costs. The discount factor to make values consistent over time is δ_t. The cost of constructing a reservoir an acre in size is c^r, and the cost of pumping an acre-foot of water from the reservoir to the field is c^{rw}.

The problem is to maximize net benefits of farm production:

$$\max_{FR_{ij}(t),RW_i(t),GW_i(t),RS_i(t)} : \sum_{t=1}^{T}\delta_t\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\left(pr_j y_{ij} - ca_j\right)L_{ij}(t) - c^r FR_{ij}(t) - c^{rw}RW_i(t) - GC_i(t)GW_i(t)\right) \quad (7)$$

subject to:

$$L_{ij}(0) = L_0^{ij}, R_i(0) = 0, AQ_i(0) = AQ_0^i \quad (8)$$

$$FR_{i1}(t) \geq 0, L_{ij}(t) \geq 0, AQ_i(t) \geq 0 \quad (9)$$

and the spatial dynamics of land and water use (Eqs. 1-6). The objective (Eq. 7) is to determine $FR_{ij}(t)$, $RS_i(t)$, $RW_i(t)$, and $GW_i(t)$, the number of acres of reservoirs, reallocation of rice acreage to irrigated soybeans, and water use, to maximize the present value of net benefits of farm production over the fixed time horizon *T*. Benefits accrue from crop production constrained by the water needed for the crops. Costs include the construction of reservoirs, the pumping of water from the reservoirs or ground, and all other production costs. Equation 8 is the initial conditions of the state variables, and Equation 9 is the non-negativity constraint on land use, reservoir construction, and the aquifer. We solve this problem with Generalized Algebraic Modeling System (GAMS) 23.5.1 using the non-linear programming solver CONOPT from AKRI Consulting and Development.

Social benefits objective

We augment Equation 7 objective to include the buffer value of groundwater. The buffer value of groundwater is defined as the ability of groundwater to mitigate undesired fluctuations in the supply of surface water. The percentage of groundwater value that is its buffer value is defined as p^{bv}. The total value of an acre-foot of groundwater is defined by v^{gw}. The net present value of the buffer value of the groundwater is:

$$p^{bv}v^{gw}\sum_{t=1}^{T}\delta_t\sum_{i=1}^{m}AQ_i(t) \quad (10)$$

The social benefits objective is then Equation 7 plus Equation 10. Benefits now accrue from crop production as well as the buffer value of the groundwater.

Data

The study area consists of three eight-digit HUC watersheds (L'anguille, Big, and the Lower White) representative of the Arkansas Delta where unsustainable groundwater use is occuring (Fig. 1). The watershed is a logical unit of analysis for tracking water supply. Urban areas and public land, where no farms are present, are removed from the study area. The watersheds overlap eight Arkansas counties that include Arkansas, Cross, Lee, Monroe, Phillips, Poinsett, Prairie, and St. Francis where groundwater use ranges from 10% to more than a 100% of the sustainable use according to the 2007 pumping rates. The study area is divided into cells roughly six hundred acres in size to evaluate how farmers make decisions about crop allocation and water use in a spatially heterogenous landscape. We use the 2010 Cropland Data Layer (Johnson and Mueller 2010) to determine the initial acreage of corn, cotton, rice and soybeans in each cell and allocated irrigated vs. non-irrigated soybean acreage on the basis of harvested acreage as reported by county for the last five years by the National Agricultural Statistics Service (http://quickstats.nass.usda.gov/).

Groundwater supply, use, and recharge

Water seepage from the reservoir into the underlying soil was estimated using soil-specific data assigned to each cell from the Soil Survey Geographic Database (SSURGO; SSS-NRCS-USDA 2012). The average saturated hydraulic conductivity (Ksat) for the soil mapping unit assigned to each cell was extracted from SSURGO. Saturated hydraulic conductivity values extracted from SSURGO were adjusted to approximate 10% of the estimated Ksat based on the soil surface texture of the soil mapping unit in each cell (Saxton et al. 1986). The adjusted Ksat values were assumed to reasonably represent the ability of unsaturated soil to transmit water over the course of one year. The hydraulic gradient was estimated based on an average of 4-acre-feet of constant ponded water at the soil surface in the reservoir and the estimated depth to the groundwater table. Annual seepage from the reservoir into the underlying soil was then estimated as the product of the unsaturated hydraulic conductivity and the hydraulic gradient.

Farm production

Cost of production data were taken from the 2012 Crop Cost of Production estimates for the crops analyzed as provided by the University of Arkansas Cooperative Extension service (http://www.uaex.edu/depts/ag_economics/budgets/2012/Budgets2012.pdf). Crop prices were the five year average of December futures prices for harvest time contracts for all crops except wheat where a September futures price is more relevant for winter wheat production (http://www.gptc.com/gptc/charts-quotes/). Irrigation extension publications on fuel use by pumping depth were used to modify cost per acre foot of water pumped as a function of pumping depth.

Reservoir construction

On-farm reservoir construction costs per acre for various size reservoirs where estimated using MARORA (http://agribus.uark.edu/2893.php; Wailes et al. 2004) and subsequently cost per acre was regressed against acres occupied by the reservoir to determine investment cost for different size reservoirs. Since a majority of the construction costs 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.

Results

For the study region, baseline conditions for farm profitability, acreage allocation, reservoir and groundwater use as well as aquifer level in acre feet and depth to the aquifer are shown in the left-most column in Table 3. Note that we assume zero reservoir water use in the base line to highlight effects of the potential for reservoirs. This is a function of both the scarcity of available data on existing reservoirs and their capacity at the spatial detail needed for this analysis as well as the objective to highlight how construction of surface water reservoirs for both recharge (note annual recharge per acre of reservoirs was estimated at an average of 10 acre feet (Table 2)) and water conservation are important to farm profitability and potential maintenance of groundwater.

Assuming producers do not avail themselves of the opportunity to build reservoirs, column B in Table 3, a significant shift away from rice production was noted over a 30 year period. Some of the rice acreage shifted to irrigated soybean whereas the remainder of curtailed irrigation was a result of shifting irrigated production to non-irrigated soybean, an activity which is more or less a breakeven proposition pending spatial yield estimate. The average depth to the aquifer increases from 69 to 85 ft which also has the effect of raising pumping costs per acre-foot by $2.24 as more fuel is needed to lift water a greater distance. Simultaneously the aquiver level declines by 22.2 million acre feet over the study region in 30 years and annual farm profitability declines from $187 million to $33 million not accounting for changes in non-irrigation related cost of production, commodity price or yield changes.

Alternatively, when reservoir construction is allowed in the model, column A in Table 3, 115,000 acres of cropland are converted to reservoirs, rice acreage still declines by 43,000 acres and irrigated soybean production increases by 7,000 acres indicating that approximately one third of the acreage needed for reservoirs came from rice acreage whereas the remainder was converted from the least profitable of the other cropland activities (non-irrigated soybean). Importantly, groundwater use is significantly curtailed from an annual 1.9 million acre feet in 2012 to 160,000 acre feet by 2042 or nearly twelvefold. The aquifer level still declines by approx. 6.1 million acre feet over the region but at nearly a fourfold slower rate than without reservoir construction (column B). Annual farm profitability still declines significantly to $58 million given the cost of reservoir building, higher pumping costs ($0.56 per acre-foot) as average pumping depth increases from 69 to 73 ft and fewer rice acres, the most profitable among crop land use activities in the region. The upshot of these two extremes is that reservoir construction is essential for the survival of rice production in Arkansas.

When the cost of water use is elevated to reflect the buffer value of the aquifer as in columns C and D in Table 3, the results are remarkably similar. Under the no-reservoir scenario, column D, more land is moved to non-irrigated production than under column B and more of the aquifer remains at the end of 30 years than if no buffer value is attached to the aquifer. Under the reservoir scenario, column C, rice and irrigated soybean acreage are marginally smaller than under column A, more acreage is diverted from other crop land uses to reservoirs and ground water use is essentially eliminated allowing for some recharge of the aquifer by adding approximately 80,000 acre feet to the aquifer from recharge associated with nearly 133,000 acres in reservoirs. Compared to column A, the added loss in annual farm profitability of $1 million is sufficient to maintain the size of the aquifer.

Figure 2 demonstrates the above trends but shows greater spatial detail. Most reservoir building occurs where pumping was least sustainable to start with and where the relative profitability of rice was highest (Panel A in Figure 2 shows Phillips county with least reservoir building as the profit differential between rice and irrigated soybean is only $45/ac compared to more than $100/ac for all other counties). Panel B in Figure 2 shows the highest aquifer decline where initial saturated thickness was highest (Figure 3) and therefore groundwater use was least worrisome. It also shows areas where groundwater level rises over time as a function of reservoir recharge capability and initial saturated thickness. Finally, Panel C shows water decline when reservoirs are not constructed which leads to drastic crop acreage reallocation.

Figure 4 shows a markedly heavier shift to irrigated soybean without reservoir construction as rice acreage demands three times the level of water compared to irrigated soybean. A notable exception is the northern region in the bottom right panel where rice and irrigated soybean production had to be replaced by non-irrigated soybean production in a region where initial saturated thickness was lowest and hence irrigated production was essentially eliminated.

Conclusion

A model was constructed to allow analysis of crop allocation changes as ground water resources continue to decline in the production region analyzed. Important drivers for change are the initial saturated thickness of the aquifer, the profit differential between competing irrigated crops (rice vs. soybean in this case) and the recharge function of reservoirs. Construction of reservoirs has the potential to significantly modify producer income as reported in the NPV of farm income values presented in Table 4 and minimizes the spread between outcomes as the aquifer buffer value plays a smaller role when groundwater resources are maintained.

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

Variable	Definition	Mean	Std. Dev.	Sum
$L_{i,corn}$	Initial acres of corn	18	47	52,661
$L_{i,rice}$	Initial acres of rice	123	116	365,955
$L_{i,cotton}$	Initial acres of cotton	28	79	82,966
$L_{i,irr\ soy}$	Initial acres of irrigated soybean	184	103	547,770
$L_{i,non\text{-}irr\ soy}$	Initial acres of dryland soybeans	59	63	174,326
$L_{i,other\ crop}$	Initial acres of other crops	32	45	95,065
$L_{i,natural}$	Initial acres of natural land	24	72	72,306
$y_{i,corn}$	Corn yield (bushels per acre)	156	8	-
$y_{i,rice}$	Rice yield (cwt per acre)	69	3	-
$y_{i,cotton}$	Cotton yield (lbs per acre)	964	74	-
$Y_{i,irr\text{-}soy}$	Irrigated soybean yield (bushels per acre)	42	3	-
$y_{i,non\text{-}irr\ soy}$	Non-irrigated soybean yield (bushels per acre)	26	4	-
dp_i	Depth to aquifer (feet)	69	29	-
AQ_i	Initial aquifer size (acre-feet)	31,369	12,688	93,259,743
r_i	Aquifer recharge from an acre reservoir (acre-feet)	4	1.6	-

Number of sites: 2,974

Table 2. Values of model parameters.

Parameter	Definition	Value
pr_{corn}	Price of corn ($/bushel)	5.07
pr_{rice}	Price of rice ($/cwt)	14.06
pr_{cotton}	Price of cotton ($/lbs)	1.02
pr_{soy}	Price of soybeans ($/bushel)	11.56
ca_{corn}	Production cost of corn ($/acre)	644.7
ca_{rice}	Production cost of rice ($/acre)	692.3
ca_{cotton}	Production cost of cotton ($/acre)	759.7
$ca_{irr\ soy}$	Production cost of irrigated soybeans ($/acre)	354.3
$ca_{non\text{-}irr\ soy}$	Production cost of non-irrigated soybeans ($/acre)	299.1
wd_{corn}	Irrigation per acre corn (acre-feet)	1.16
wd_{rice}	Irrigation per acre rice (acre-feet)	3.34
wd_{cotton}	Irrigation per acre cotton (acre-feet)	0.84
$wd_{soybean}$	Irrigation per acre soybean (acre-feet)	1.00
δ_t	Discount factor	0.95
c^r	Estimated per acre cost of reservoir construction ($/acre)	743*
c^{rw}	Cost of pumping water from the reservoir ($/acre-foot)	6.60
c^p	Cost to lift an acre-foot of water a foot using a pump ($/foot)	0.14
ω	Water held by a full one acre reservoir (acre-feet)	12
v^{gw}	Total value of groundwater ($/acre-foot)	4.89
p^{bv}	Percentage of groundwater value that is buffer value	38%

***** This is an average cost of construction of a multi-acre reservoir. The first acre of the reservoir constructed is likely to be much more expensive.

Table 3. Initial and final crop allocations and water conditions with and without buffer value consideration and with and without the construction of reservoirs, Three Watersheds in Arkansas**.**

Crop and water conditions	**Initial, 2012 Baseline**	**Without Buffer Value**		**With Buffer Value**	
		Final, with reservoirs, 2042 (A)	**Final, without reservoirs, 2042 (B)**	**Final, with reservoirs, 2042 (C)**	**Final, without reservoirs, 2042 (D)**
Rice (thousand acres)	366	323	1	322	0.5
Irrigated soy (thousand acres)	548	555	581	551	426
Irrigated crops (thousand acres)	1,049	1,013	701	1008	542
Non-irrigated soy (thousand acres)	267	188	615	175	774
Reservoirs (thousand acres)	0	115	0	133	0
Reservoir water (thousand acre-feet)	0	1604	0	1753	0
Groundwater (thousand acre-feet)	1901	160	695	3	539
Aquifer (thousand acre-feet)	93,260	87,163	71,060	93,341	77,120
Average depth to aquifer (feet)	69	73	85	69	80
Annual farm net benefits ($ millions)	187	58	33	57	31

Table 4. Change in the value of farm net benefits under Profit Maximization with and without a buffer value for groundwater and with and without the construction of reservoirs.

	30 Year NPV of Farm net benefits ($ Millions in 2012 dollars)	
Objective	**Reservoirs**	**No Reservoirs**
without Buffer Value (a)	2,081	1,214
with Buffer Value (b)	2,034	1,149
Ratio of (a) to (b)	1.02	1.06

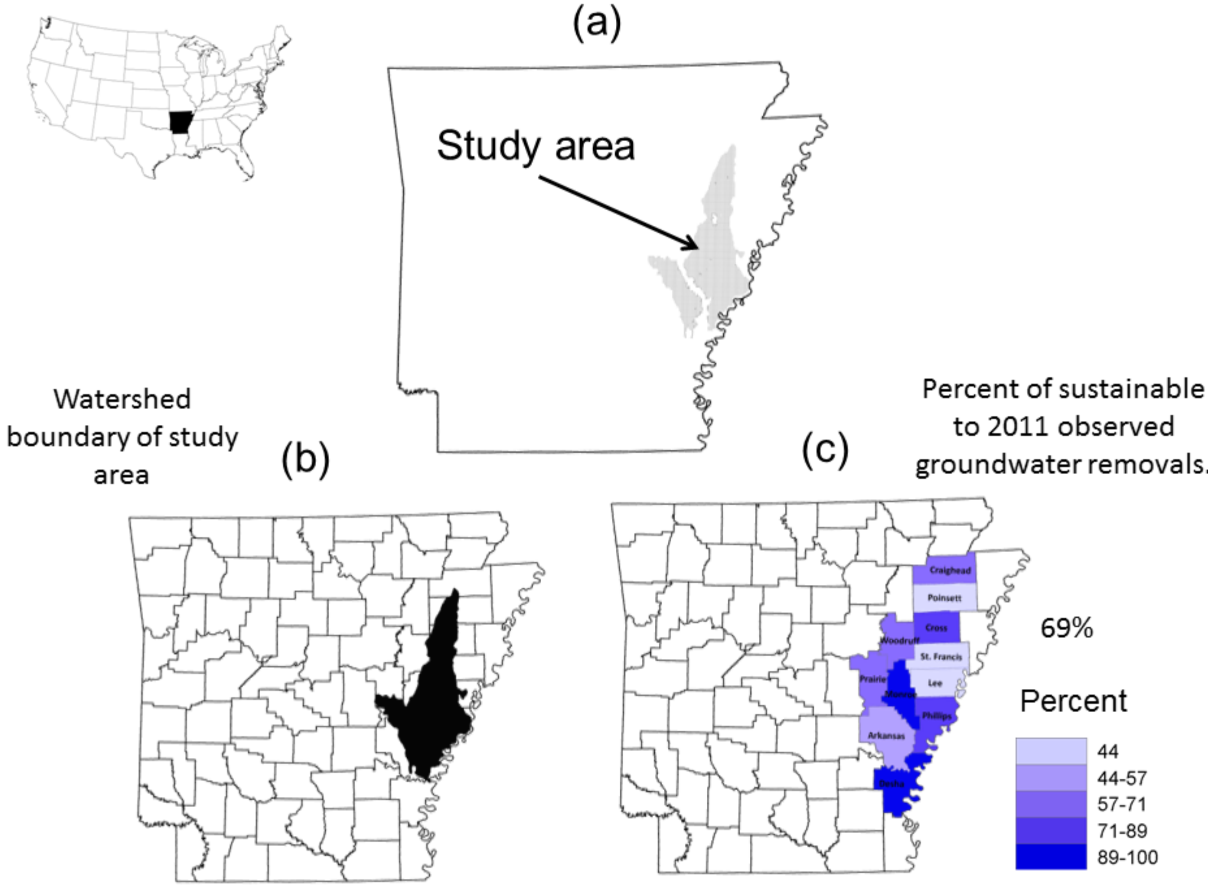

Figure 1. (a) Study area shown as grid cells. Public land and urban area are excluded. (b) The three watersheds (eight-digit hydrologic unit code) that define the outer boundary of the study area are shown over the boundaries of the Arkansas counties. (c) The percentage of sustainable groundwater removals to the groundwater removals observed in 2011. Darker shades indicate that county-wide removals of groundwater are more sustainable. The number by the side of the map indicates the study area averages.

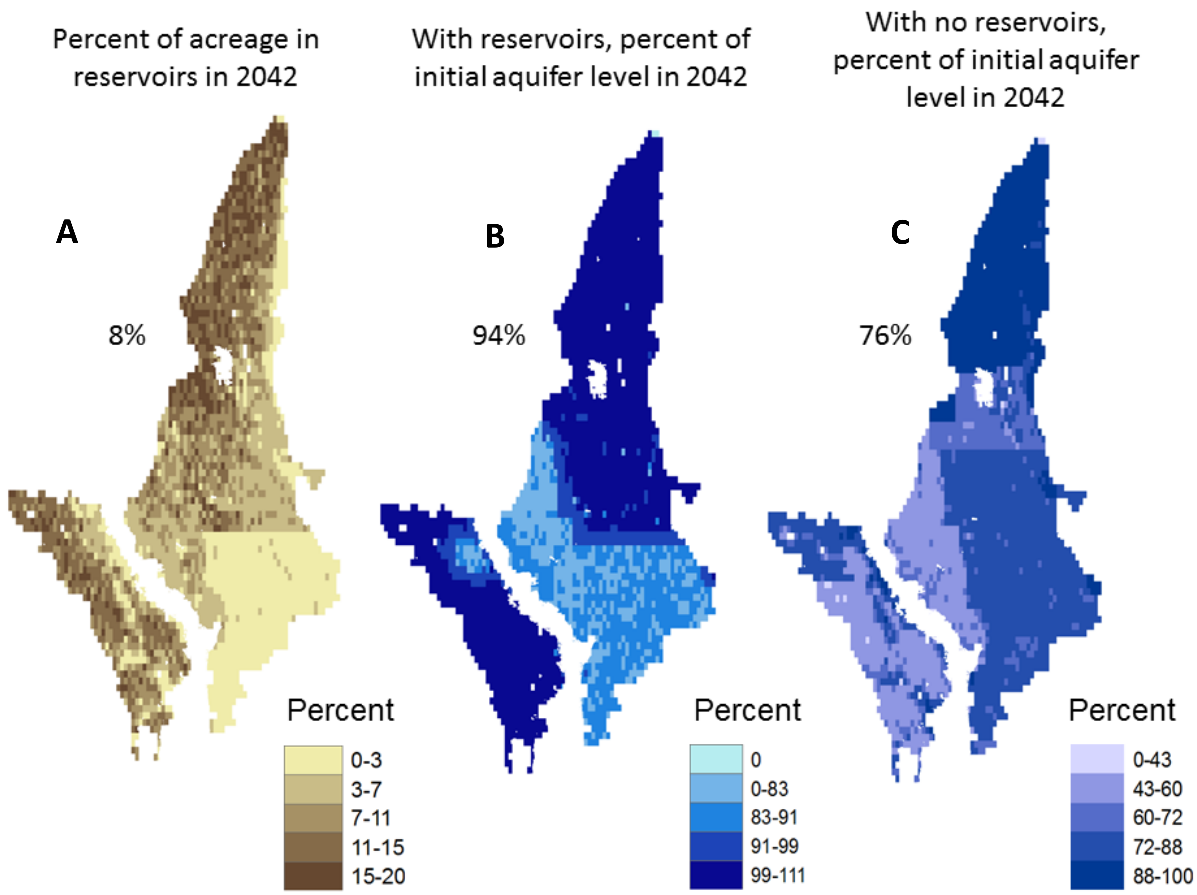

Figure 2. Percentage of acres at each site converted to on-farm reservoirs shown to the left. The maps to the center and right show the percentage of the initial groundwater remaining in the aquifer in 2042 with and without the construction of reservoirs. Greater than a hundred percent is possible with the reservoirs due to recharge from the reservoirs. The numbers by the side of each map indicate study area averages.

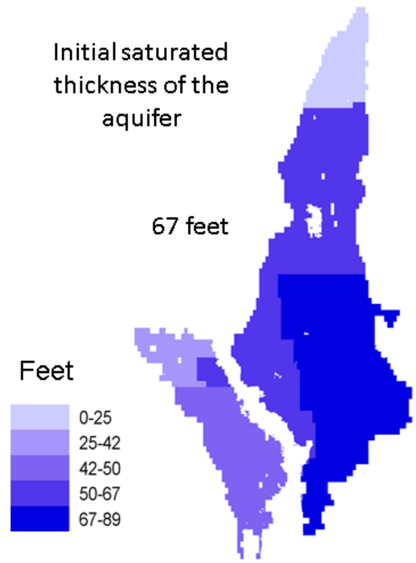

Figure 3. Saturated thickness of the aquifer shown for 2012. The number by the side of the map indicates study area average.

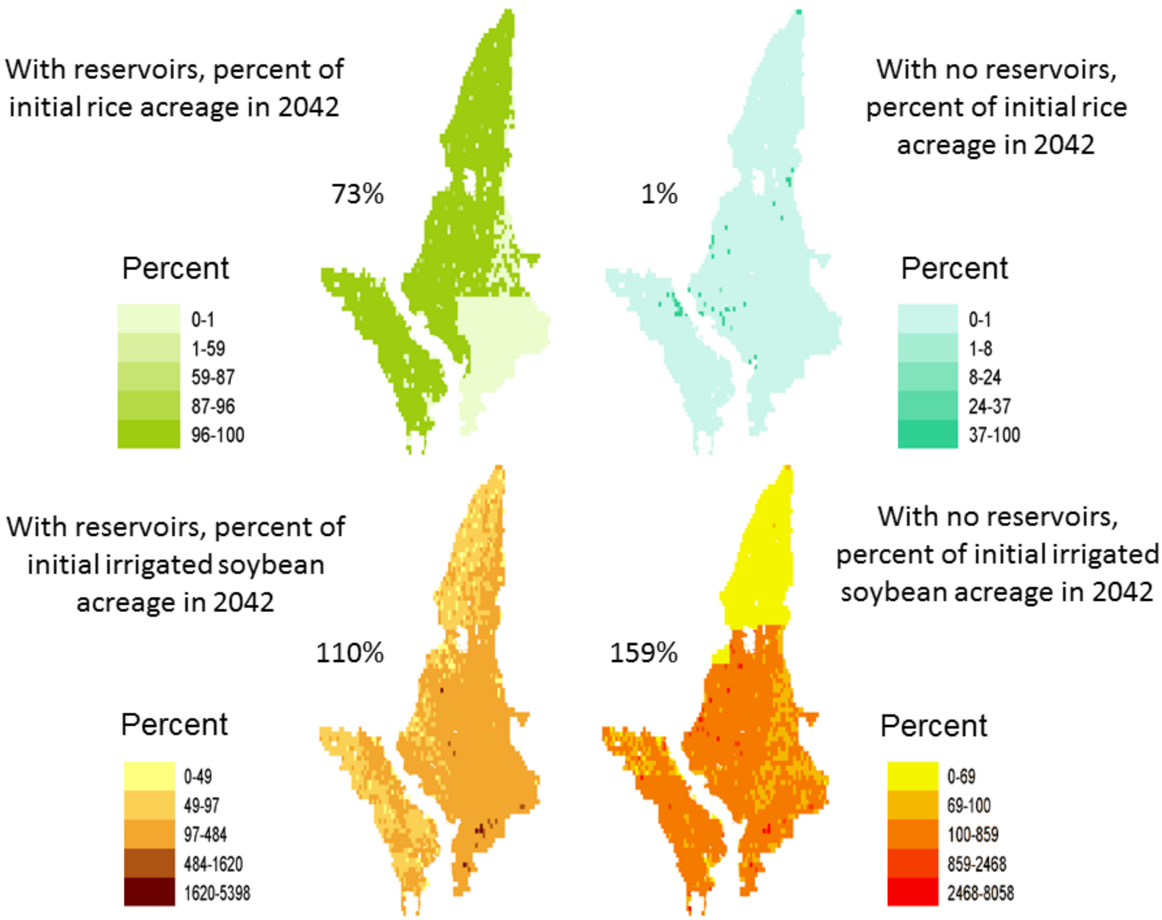

Figure 4. Top row indicates the percentage of initial acres in rice at each site still in rice acreage in 2042 with and without the construction of reservoirs. Bottom row indicates the percentage of initial acres in irrigated soybean at each site still in irrigated soybean acreage in 2042 with and without the construction of reservoirs. A decline in irrigated soybean acreage can occur without reservoirs because the land converts to non-irrigated soybean. The numbers by the side of each map indicate study area averages.