

Research papers

Long run optimization of landscape level irrigation through managed aquifer recharge or expanded surface reservoirs

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ABSTRACT

Decades of efforts to reduce groundwater overdraft through investment in irrigation efficiency has, in many cases, failed to reduce aquifer depletion. This is one reason for greater attention to water supply augmentation efforts through the capture of surface water during high flow events for managed aquifer recharge (MAR) or additional surface storage. We use a landscape level model to examine the optimal interaction among MAR, surface reservoir storage, crop choice, and groundwater conservation policies in Eastern Arkansas. We find the cost of MAR water must be less than half the average groundwater pumping cost to increase the aquifer level. Increases in irrigation intensive crops mean that only a fraction of the recharged water raises groundwater levels. We observe that policies to conserve groundwater, such as a pumping cap or tax, are more cost-effective for society with a lower cost of MAR water.

1. Introduction

Falling groundwater levels raise the future costs of well pumping for irrigation and diminish the resilience of agriculture to drought. Over the past century, the average annual groundwater depletion in the United States was about 6.5 million acre-feet, and this average rose to 19.4 million acre-feet from 2001 to 2008 (Konikow, 2013). Reducing withdrawals by increasing irrigation efficiency alone is not an adequate solution for the sustainable management of groundwater (Pfeiffer and Lin, 2014; Grafton et al., 2018). Instead many regions conjunctively use surface and groundwater (Harou and Lund, 2008; ANRC, 2017). One type of conjunctive use is the storage of excess surface water in aquifers through managed aquifer recharge (MAR) rather than in surface reservoirs (Harter and Dahlke, 2014; O'Geen, 2018). However, no studies optimize whether MAR can economically complement traditional irrigation sources, such as groundwater or surface reservoirs. The traditional supplies are likely cheaper initially, but the role of MAR in irrigation could become prominent as those sources become unavailable or prohibitively expensive.

Our study fills three major knowledge gaps in the literature by optimizing economic returns through the spatial-dynamic interaction of MAR, traditional irrigation sources, and crop choice. First, the optimization of economic returns is relevant because this is how farm irrigators, the principal water users, make their decisions. The optimization

then provides a useful guide for how the irrigators might use MAR over time and across the landscape as the expense of traditional irrigation sources rise. Second, crop choice allows switching between crops of varying irrigation intensity, and this can lead to a slippage effect, which is when the use of MAR stabilizes groundwater levels, causes a switch to irrigation intensive crops, and increases groundwater pumping (Grafton et al., 2018). The slippage effect occurs with the use of efficient irrigation practices (Pfeiffer and Lin, 2014; Adams and Kovacs, 2019) and the conjunctive use of surface reservoirs (Kovacs and Durand-Morat, 2017), but no study examines if and how much this occurs with MAR. Third, since the study of MAR through optimization is new, our analysis examines how sensitive optimal MAR use is to crop profitability, initial groundwater depths, and groundwater conservation policies, which is of potential interest to water managers and policy makers.

Traditionally the construction of surface reservoirs allows for the storage of water during the wet season for dry season uses. However, reservoir storage can be expensive, occupy valuable land, and most of the optimal locations for reservoirs are already developed (Scanlon et al., 2016; Brown et al., 2019). Surface water reservoirs are also less attractive if heat waves from climate change shift snowpack runoff to the early spring when demand is low (Barnett et al., 2005), or more intensive rainfall leads to flood water that reservoirs do not have the capacity to store (Najibi et al., 2017). Instead, excess water could be put into depleted aquifers to increase sustainable groundwater yields

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(Bouwer, 2002). Aquifer storage methods include injection through wells, shafts, and boreholes, spreading over fields, induced bank filtration, and in-channel or reservoir modifications (Hannappel et al., 2014). MAR can increase groundwater supplies to buffer against climate extremes in the future, and water agencies use MAR in many parts of the world (Niswonger et al., 2017; Scherberg et al., 2014, 2018). However, MAR through injection wells is often less economically feasible than surface reservoirs because there is a large expense to clean and pump water into the aquifer. Also, the use of MAR through infiltration basins means there are expenses for land and maintenance of the basins. All MAR approaches mean there is a future expense to pump the water back out of the aquifer.

Recent research highlights the use of MAR to sustain agricultural production (Harter & Dahlke, 2014; Scanlon et al., 2016; O'Geen, 2018). However, most of this research focuses on the technical suitability of MAR with geographic information systems (Ahani Amineh et al., 2017; Smith et al., 2017; Gibson et al., 2018) or hydrologic models (i.e., Modflow (Niswonger et al., 2017; Scherberg et al., 2014, 2018) rather than economic feasibility. MAR is a type of conjunctive use that directs excess surface water to aquifer storage rather than surface reservoirs (Evans and Evans, 2011; Dillon and Arshad, 2016). When the capacity of surface reservoirs is met, excess water can be directed into the aquifers. Spatial variability in the hydrologic and agronomic conditions of a landscape then determine where and when MAR is economically feasible (Maliva, 2014, 2015; Dillon and Arshad, 2016).

Although MAR is technologically feasible (Kresse et al., 2014), little is known about the effects of MAR on groundwater pumping, land use, and the economic returns on an agricultural landscape. Nor do earlier studies examine, as our study does, the trade-offs in the role of groundwater augmentation, through on- and off-farm surface storage and MAR, to maximize economic returns through conventional and efficient irrigation practices. Marques et al. (2010) Balali et al. (2011) and Pulido-Velazquez et al. (2011) analyze groundwater conservation technologies and multiple crops while comparing objectives such as aquifer conservation and economic returns. Marques et al. (2010) use two-stage stochastic quadratic programming to optimize conjunctive water use of groundwater pumping and artificial recharge with cropping and irrigation technology decisions for an irrigation district in California. Marques et al. (2010) rely on the assumption of a single, large aquifer and a negligible change in the groundwater table and pumping cost for the entire irrigation district. Also, their model of the aquifer assumes an instant and uniform response to pumping over the entire extent, and this representation for the aquifer significantly underestimates the magnitude of the groundwater pumping externality (Brozović et al., 2010). Balali et al. (2011) use a non-linear optimization model to analyze the impacts of irrigation water pricing and agricultural policy scenarios on aquifer conservation. Although, the recharge volume in their model was not chosen through optimization. Pulido-Velazquez et al. (2011) propose a downscaling approach to generate future climate indices, and incorporate those indices into the SIMES and AQUATOOL, process-based simulation models, to examine conjunctive-use water management. MAR is a component of the model, but MAR is not chosen through an optimization model. Other economic MAR studies do not consider how to spatially optimize artificial recharge for a landscape.

Our study region for the optimal use of excess water for surface reservoirs or MAR through injection wells is Eastern Arkansas, USA. Arkansas is the largest user of water for irrigation from the Mississippi Valley Alluvial Aquifer, the third most used aquifer in the United States (Konikow, 2013). The region receives an abundant 45–50 in. of rainfall per year (Clark and Hart, 2009), but this mostly occurs in the winter and spring seasons before the crop's major water demand, and this makes the storage of the seasonal rainfall an attractive prospect. Based on the legal definition of excess surface water for the state, there is more than 5.5 million acre-feet/year (or 85% of all irrigation water applied in the state in 2013) of excess surface water that can be withdrawn from two major rivers in the region (ANRC, 2014; USDA-NASS, 2013).

Groundwater use in Arkansas supports the largest rice production in the United States in addition to other irrigated crops, especially soybeans but also corn and cotton. A substantial rise in the number of irrigated acres has meant a tenfold increase in the use of groundwater for irrigation between 1950 and 2010 (Kresse et al., 2014). Cones of depression in the groundwater level surface have led to the designation of critical groundwater areas in the state (ANRC, 2005, 2017). We examine whether irrigators choose between groundwater pumping that results in lower water levels and higher pumping costs, surface reservoirs constrained by capacity, and MAR constrained by the maximum injection rate and water conveyance and cleaning costs from surface water sources to injection sites. This in turn influences farm decisions across the landscape for crop choice and irrigation practices. Particular attention is given to the relationship between the irrigation intensity of the chosen crops and the surface reservoir and MAR water costs, MAR recovery efficiencies, and the occurrence of drought.

2. Methods

We use non-linear optimization to maximize the present value of net returns from farm production over an entire time horizon through the choice of multiple crops, MAR water use, and on- and off-farm surface water use for a couple thousand sites on a landscape. Other than the well pumping component, the model is linear in the choice variables. Our aim is to consider how the detailed spatial and temporal dimensions of a deterministic model influence crop and water source choices. We assume that farm producers collectively optimize profits and perfectly foresee future market and environmental conditions to keep the focus on the tradeoffs between the optimal planner's use of MAR and other water sources. The baseline model supposes that there is no use of MAR, and we compare model outcomes without MAR to the outcomes with MAR for a range of MAR costs. Sensitivity analyses of the baseline model with MAR evaluate the robustness of MAR use, net returns, and aquifer conservation to changes in key parameters.

2.1. Land use choices

The landscape is spatially heterogeneous in groundwater resources and crop yields (ANRC, 2017; USDA-NASS, 2018a). There are many potential remedies to groundwater overdraft, and our model considers surface water storage with on-farm reservoirs or off-farm water (water stored in surface reservoirs) deliveries, non-irrigated crops/idle crop land, and more efficient irrigation practices. There are, m , land uses that include the following crops: rice, irrigated soybean, corn, and cotton, non-irrigated soybean and double cropped irrigated soybean with winter wheat. Two other land uses include following the land or constructing on-farm reservoirs. An on-farm reservoir built on a unit of land permanently remains as a reservoir for the duration of the study period. These crops may use, k , irrigation practices, namely conventional (contour-levee flood for rice and flexible poly-pipe furrow for other crops), conservation furrow (the use of soil sensors and computerized hole-selection software for calculating punched hole sizes in flexible poly-pipe), and zero-grade leveling flood for rice (Hignight et al., 2009; Henry et al., 2016; Mississippi State University, 2016a,b). Each year, t , a producer at farm site, f , chooses to allocate, $A_{fi}(t)$, acres to land use, l , and irrigation practice, i .¹ Eq. (1) indicates that the sum of the land in all uses and irrigation practices must equal the amount of land, A_f , suitable for agriculture at site, f , in the initial year:

¹ There is typically a mix of crops in each cell each year that reflects the crops grown in rotation, based on the historical land use, but there is no constraint that crop types switch every year. There are sixteen crop and irrigation practices choices. Each year, a site can have more than one crop and irrigation choice.

$$\sum_l^m \sum_i^k A_{fli}(t) = A_f, \text{ for all } t. \quad (1)$$

Any land use l other than an on-farm reservoir can become another land use in the subsequent period constrained by minimum and maximum amounts of the land use based on historical land use patterns.

2.2. Irrigation

The irrigation water demand per crop, $w_{r_{fi}}$, is the irrigation water applied per unit of land at site f to crop l with irrigation practice i . Confronting groundwater shortage, we assume producers switch to less intensively irrigated crops rather than deficit irrigate an intensively irrigated crop. Empirical evidence from Moore et al. (1994) and Wang and Segarra (2011) suggests that perfectly inelastic demand for irrigation water is a reasonable assumption even in the long run. Pumping equipment changes can address seasonal problems of groundwater overdraft over the long run. Seasonal overdraft is an important consideration for the timing of groundwater pumping within a year but less important to choices over a century. The total irrigation demand at each site is $w_{r_{fi}}$ multiplied by the amount of land in each irrigated crop, l , which equals the sum of groundwater use, $GW_f(t)$, off-farm surface reservoir water use, $OW_f(t)$, and on-farm reservoir water use, $RW_f(t)$ as shown in Eq. (2),

$$\sum_l^m \sum_{i=1}^k w_{r_{fi}} A_{fli}(t) = GW_f(t) + OW_f(t) + RW_f(t). \quad (2)$$

The water in an on-farm reservoir depends on the recovery of runoff from irrigation and precipitation. Kovacs et al. (2014) express the water held by a unit of land in a reservoir as $(\omega_{fr} + \omega_{fw}) - \omega_{fr} \left(\frac{A_{fr}(t)}{A_f} \right)$ where ω_{fr} and ω_{fw} are the water recovered to a unit of reservoir land from irrigation and precipitation, respectively, and $A_{fr}(t)$ is the total land in an on-farm reservoir at site f in time t . As the reservoir occupies a larger proportion of the field, then the irrigation component diminishes until the water in the reservoir is only from precipitation, ω_{fw} .

2.3. Groundwater level and maximum MAR injection rates

Groundwater flow depends on forward difference approximation to solve a combination of Darcy's law and the continuity equation i.e., Laplace's equation (Wang & Anderson, 1982). The water level at site, f , in year $t + 1$, $H(t + 1)$, depends on the water level in year t , $H(t)$, storativity, S , the size of the site, A_f , the sources and sinks which include the natural recharge, $NR_f(t)$, the use of water for managed aquifer recharge, $MAR_f(t)$, scaled by a recovery efficiency, $RE_f(t)$, the groundwater extraction, off-farm and on-farm surface reservoir application, and a return flow coefficient α . Each site has a finite initial reserve of groundwater available to irrigators, and we assume that each site has a single well at the center that can be used for both groundwater pumping and MAR. MAR only occurs through the well injection because the study area has a relatively thick confining unit (more than 10 feet), which makes recharge through infiltration basins less effective due to the expense of removing the confining units (Fitzpatrick, 1990).³

The recovery efficiency, $RE_f(t)$, which indicates the proportion of recharge water not lost to surface water bodies or other aquifers, scales the MAR. The net change in the volume of water due to human

intervention at site, f , $NR_f(t) + RE_f(t)MAR_f(t) - (1 - \alpha)GW_f(t) + \alpha(RW_f(t) + OW_f(t))$, where the groundwater use scales by $1 - \alpha$, to account for a portion of the applied groundwater pumping returning to the aquifer, and the surface water use from on-farm storage, $RW_f(t)$, or off-farm delivery, $OW_f(t)$, which scales by the proportion of return flow, α . The storativity area of the aquifer, $A_f S$, divides the change in the volume of water in the aquifer to calculate the change in the water level shown in Eq. (3),⁴

$$H_f(t + 1) = H_f(t) - \frac{NR_f(t) + RE_f(t)MAR_f(t) - (1 - \alpha)GW_f(t) + \alpha(RW_f(t) + OW_f(t))}{A_f S}. \quad (3)$$

The maximum amount of MAR water for injection into the aquifer at each cell depends on the hydraulic properties (Theis, 1935) and the evidence from actual recharge tests (Fitzpatrick, 1990). Cooper and Jacob (1946) simplified the Theis equation for large values of time, t , and/or small values of well radius, r , to be Eq. (4)

$$h_{fw} - h_{f0} = \frac{2.3MAR_f(t)}{4\pi T_f} \log \frac{2.25T_f t}{r^2 S}, \quad (4)$$

where h_{fw} is the hydraulic head undergoing injection and h_{f0} is the initial hydraulic head prior to injection. T_f is the transmissivity, which equals the saturated thickness multiplied by horizontal hydraulic conductivity ($T_f = K_f b_f$).

A well is suitable for well injection if $\frac{DTW_f}{h_{fw} - h_{f0}}$ is equal to or greater than one, where DTW_f is the depth to static water level below the ground surface (Gibson et al., 2018). When the maximum amount of water is injected, $\frac{DTW_f}{h_{fw} - h_{f0}}$ is equal to one. Solving for MAR on the right hand side of Eq. (3), when $\frac{DTW_f}{h_{fw} - h_{f0}}$ is set equal to one, indicates maximum annual injection rate for the site.

2.4. Total net returns objective

The irrigation and land use choices that maximize profitability depend on input costs, crop prices, and the groundwater level. The total cost of MAR water, $C^{ar}(t)$, is the per unit cost of MAR water, which consists of fixed costs, c_f^{arfix} (e.g. pipeline, canal, pumps and other infrastructure and equipment costs), and variable costs c_f^{arvar} , (e.g. principally energy costs to transport the water to the injection well and inject water in to the aquifer⁵ (FEMA, 2016; Gibson et al., 2018) multiplied by the total volume of injected MAR water (Eq. (5)).

$$C^{ar}(t) = \sum_f^n (c_f^{arfix} + c_f^{arvar})MAR_f(t). \quad (5)$$

Similarly, the total cost of off-farm surface storage water, $C^{ow}(t)$, is the per unit cost of off-farm water, c_f^{ow} , which includes fixed costs (e.g. siting and land purchases in addition to infrastructure and equipment) and variable costs, multiplied by the volume of off-farm water (Eq. (6)):

$$C^{ow}(t) = \sum_j^n c_j^{ow}OW_j(t) \quad (6)$$

The total cost of groundwater pumping, $C^{gw}(t)$, depends on the cost

² In the eastern Arkansas, previous studies show that 93% of farmers used groundwater from the Mississippi River Valley alluvial aquifer (locally referred to as Alluvial aquifer) during 1985–2010 (USGS, 2018), and thus we assume that groundwater for irrigation comes only from the Alluvial aquifer.

³ There is a growing interest in identifying sites where the confining layer is thin enough to permit infiltration MAR, which is less expensive, but there is insufficient information on the underlying soil and geologic properties of the landscape to evaluate this option.

⁴ The first section of the supporting information describes the calibration to the historical change in groundwater levels.

⁵ We assume that a farmer uses bank infiltration to extract surface water through extraction wells and transport/convey water to injection wells. The concept is to induce flow through the streambed into the aquifer and capture that water, rather than groundwater from storage, and use a pipeline to transfer water to where MAR is needed, and inject the water into the aquifer using injection wells. Additional description of the cost components for surface water delivery is in the second section of the supporting information.

to lift one unit of water by one unit of depth, c_f^{gw} , multiplied by the depth, $H_f(t)$, plus the capital costs per unit of water extracted for the well, which accounts for new well drilling in response to aquifer decline, c_f^{pw} , multiplied by the volume of groundwater pumped (Eq. (7)):

$$C_f^{gw}(t) = \sum_f^n (c_f^{pw} H_f(t) + c_f^{gw} GW_f(t)). \quad (7)$$

The total cost of pumping from on-farm reservoirs, $C_f^{rw}(t)$, is shown in Eq. (8) as the cost of pumping a unit of water from an on-farm reservoir, c_f^{rw} , multiplied by the reservoir water in use plus the capital and maintenance cost of a unit of reservoir land for each period, c_f^{rw} , multiplied by the reservoir area built:

$$C_f^{rw}(t) = \sum_f^n (c_f^{rw} RW_f(t) + c_f^{rw} A_{fr}(t)). \quad (8)$$

Given the time horizon, T , the model maximizes the total net return over all n farm sites, which have variation in land use, hydrologic conditions and the costs of surface water conveyance for MAR water. The price of crop l is p_l ; the yield of crop l planted at site f with irrigation practice i is y_{fli} , and the production cost of crop l with irrigation practice i is c_{li} . The real discount factor in year t is δ_t . The objective is to maximize the present value of net returns shown in Eq. (9) as

$$\max_{\substack{A_{fli}(t), RW_f(t), \\ OW_f(t), GW_f(t), \\ MAR_f(t)}} \sum_t^T \delta_t \left(\sum_f^n \sum_l^m \sum_i^k ((p_l y_{fli} - c_{li}) A_{fli}(t) - C_f^{ar}(t) - C_f^{ow}(t) - C_f^{gw}(t) - C_f^{rw}(t)) \right) \quad (9)$$

subject to the non-negativity constraints in Eq. (10):

$$A_{fli}(t) \geq 0, RW_f(t) \geq 0, OW_f(t) \geq 0, GW_f(t) \geq 0, MAR_f(t) \geq 0, \quad (10)$$

and the spatial dynamics of land, irrigation and artificial recharge (Eq. (1)–(4)).

2.5. Sensitivity analyses

The cost of MAR water and off-farm water are largely unknown because the fixed costs depend on unspecified plans for the water delivery infrastructure.⁶ We therefore assume a range for the fixed capital costs (e.g., infrastructure, equipment, and interest) that are paid for equally across all the farm sites. The variable water conveyance costs depend on the distance to a river with an approved excess surface water allocation and the volume of the water delivery. Due to the variability of recharged water recovery (Scherberg et al., 2014; Webb, 2015), we also evaluate the economic feasibility of MAR for recovery efficiency at both 60% and 100%. Some model runs consider the presence of drought because this could change the proportion of water for MAR relative to other irrigation sources. Other sensitivity analyses examine the model outcomes in response to 50% higher and lower crop margins, initial depths to groundwater, and the real discount rate. Crop margin changes reflect three types of movements that occur regularly from market forces: crop prices, yields, or production costs. Also, the use of water for MAR is responsive to the initial depth to the groundwater and the real discount rate.

2.6. Groundwater policies

MAR in conjunction with groundwater conservation policies could more cost effectively curtail overdraft. A pumping cap of 75% of current pumping at a MAR water cost of \$20/acre-foot is a compromise between political feasibility and the more stringent cap necessary for the sustainable yield of the aquifer (ANRC, 2017). Additional pumping beyond

what the cap allows is possible each period if MAR completely replaces, for that period, the excess groundwater pumping. The pumping cap at a MAR water cost of \$40 and \$60/acre-foot is set to achieve a level of groundwater conservation similar to the 75% pumping cap at a MAR water cost of \$20/acre-foot. An alternative policy is a tax to increase the groundwater pumping costs which also decreases pumping and net returns. The tax is set to achieve a level of groundwater conservation similar to the 75% pumping cap at a MAR water cost of \$20/acre-foot.

A cost-effective policy conserves a unit of groundwater at a lower social cost than any other policy. The social cost of a policy is the difference in economic returns, with the policy versus without the policy, plus the change in government tax revenue. The social cost thus indicates what society gives up to increase groundwater. This criterion does not say what the efficient level of groundwater should be but only what policies can raise the groundwater level at the lowest social cost.

3. Study location and data

Farmers in the Eastern Arkansas region (Fig. 1) rely heavily on groundwater from the Alluvial aquifer (the top most layer of the Mississippi Embayment) for irrigation because alternative water sources are uncertain or unavailable during irrigation periods (Czarnecki et al., 2002; Vories & Evett, 2010; ANRC, 2013). About 93% of groundwater withdrawals in Eastern Arkansas were for irrigation from 1985 to 2010 (USGS, 2018). Three eight-digit hydrologic unit code (HUC) watersheds delineate the study area (Fig. 1) and overlap with eleven Arkansas counties. The study area overlays critical groundwater areas (CGA), defined by the Arkansas Natural Resources Commission (ANRC) as aquifers with significant groundwater depletion and degradation (ANRC, 2005, 2017). The study period is 120 years, from 1917 to 2136, to evaluate how long term groundwater overdraft relates to the economic feasibility of MAR.

A grid of 2000 cells is overlaid on the study area to extract spatially heterogeneous information on hydrologic conditions and crop yields for the model. Each cell has a well located in the center of the site, and the total available land for crops is based on the initial year cropland. The wells are dual-purpose, useful for both recharge of surplus water in the winter and spring followed by groundwater extraction during periods of irrigation. The injection well operates in October through April, when surplus water is available, no irrigation occurs, and obtaining water rights is the most flexible (Fitzpatrick, 1990). The depth to the water table, saturated thickness, and hydraulic conductivity of the aquifer from the ANRC are site specific (ANRC, 2017). The saturated thickness allows us to calculate the limited volume of groundwater available to each site. The natural recharge values and the aquifer storativity come from U.S. Geologic Survey (Clark and Hart, 2009; Reitz et al., 2017).

Based on the geo-hydrologic conditions across the sites described in Section 1 of the Supporting information and Eq. (3), we estimate that the maximum annual injection rate for recharge across the sites varies from 155 to 6782 acre-feet per year. Also, a USGS pilot study of MAR through well injection shows that water can be injected at rates varying between 37 and 860 gallons/min (60–1400 acre-feet per year) in Eastern Arkansas (Sniegocki et al., 1965; Fitzpatrick, 1990). Combining these two independent approaches to calculating the injection rate, the maximum injection annually across injection sites is between of 155 and 700 acre-feet over non-irrigation periods.⁷

⁷ If we select a system with a capacity of 1225 gallons/min, we need to operate the recharge roughly 130 days to be able to inject 700 acre-feet. Given the temporal variation of surplus water, water quality and time of operation and maintenance of the recharge system due to well clogging, biological growth, chemical reactions between the native groundwater or aquifer materials and recharge water, precipitation of insoluble products due to aeration, and air entrainment (Sniegocki, 1963a,b, 1965), we select the maximum annual injection rate across recharge sites as between of 155 and 700 acre-feet/year even though hydrogeologic conditions in many sites can withstand a higher injection rate.

⁶ Agricultural lands in the study area that currently do not have access to off-farm surface reservoirs could receive water from planned and/or under-construction United States of Army Corps of Engineers reservoirs.

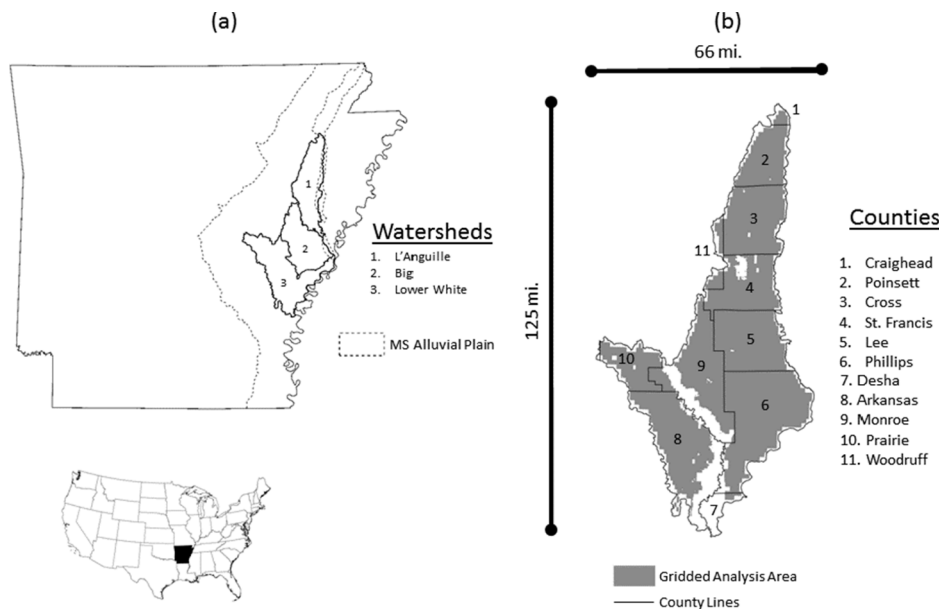


Fig. 1. Three eight-digit hydrologic unit code (HUC) watersheds in the Mississippi Delta region of eastern Arkansas define the outer boundary of the study area. An eight-digit HUC defines the drainage area of the sub-basin of a river. Map (a) indicates the location of the study area within the State of Arkansas. Map (b) shows county lines overlaying the study area. Public land and urban areas are excluded, and these blank areas in map (b) do not have grid cells.

Section 2 of the Supporting information indicates excess surface water in the region can meet the potential water demand for MAR water, even when all injection wells operate at full capacity (i.e. 700 acre-feet per year). Arkansas Natural Resources Commission estimates that there is more than 5.5 million acre-feet per year of excess surface water that is legally available from the two biggest rivers in the study area, namely the White and Arkansas Rivers. Water has to be transported from a river with excess surface water, and the MAR water cost largely depends on the capital costs to deliver water from the rivers to the recharge sites (Dr. J. Rigby and Mr. D. Pyne, personal communication, August 4, 2018). The capital costs of the planned off-farm delivery of water from the U.S. Army Corp of Engineers projects in Arkansas are highly speculative (ANRC, 2014). Since the capital costs, c_f^{arfx} and c_f^{ow} , that we suppose are the same across all the sites, are uncertain, we suppose a range from \$10 to \$100/acre-foot based on the cost of the planned projects (ANRC, 2014).

Table A1 in the third section of the supporting information has the average acreage of each crop initially by site based on the 2017 Cropland Data Layer (USDA-NASS, 2018a). The irrigated vs. non-irrigated soybean acreage is based on the harvested acreage for 2016–2017 (USDA-NASS, 2018b). The estimate of yield for each of the crops comes from the average county crop yields for the past 5 years (Division of Agriculture-UARK, 2018). The capital and operating costs for the irrigation technologies, reservoirs, MAR, wells, and the costs of production for the crops shown in Table A2 are constant over time in real terms. Also in the third section of the Supporting information is a description of adjustment coefficients to the crop irrigation demand and crop yields to alternative irrigation practices. We use a 2% real discount rate, which comes from a 5% nominal discount rate based on the 30-year treasury bond yield over the fifty years less a long-run expectation for inflation of 3% (U.S. Department of the Treasury, 2017).

A drought year described in section 4 of the Supporting information has a negative Palmer Drought Severity Indices (PDSI) value (NOAA, 2018). We make a synthetic drought record for the 120 year study period by repeating the past thirty years of historical PDSI values four times (Palmer, 1965). The reduction in dryland crop yields from drought comes from yield data for the last thirty years (USDA-NASS, 2018b), and the increase in groundwater pumping for irrigated crops due to drought comes from producers' response to the 2012 drought in Arkansas (Kemper et al., 2012). Drought typically increases irrigation by 1–2 additional inches for row crops and 5–10 additional acre-inches of water for rice (Kemper et al., 2012).

4. Results and discussion

Initially we examine the optimal amount of MAR water use for different costs of MAR water and recovery efficiencies with and without drought. We consider how much MAR incentivizes land use change to more intensively irrigated land, and we compare total net returns with MAR only versus off-farm surface storage deliveries for a range of water costs. Second, we analyze the use of MAR water and other irrigation sources for sensitivity analyses on the crop margins and initial depths to groundwater. Third, we consider how the use of MAR influences the cost-effectiveness of groundwater conservation policies.

4.1. Optimal use of water for MAR

Fig. 2 shows the use of water for MAR for different costs of MAR water and drought conditions over the 120-year study period. The recovery efficiency and cost of MAR water influence the effectiveness of using MAR water to replenish groundwater stored in the aquifer, but drought only increases the demand for MAR water considerably when the cost of MAR water is less than \$30/acre-foot. If 100% recovery efficiency is possible and the cost of MAR water is less than \$100/acre-foot, then there is well injection at some sites early in the time horizon (Fig. 2B and D). However, extensive use of MAR water only appears to occur if the cost of MAR water is less than \$60/acre-foot and the recovery efficiency is at least 60% (Fig. 2A and C). If the cost of MAR water is \$20/acre-foot, producers cumulatively inject about 35 million acre-feet of excess surface water to the aquifer with a recovery efficiency of 60% over the time horizon. At the same recovery efficiency and a cost of MAR water of \$60/acre-foot, there is only 1.3 million acre-feet that producers cumulatively inject to the aquifer or about 5.42 acre-feet/year at each injection well. This finding is consistent with previous studies that show artificial recharge is not widely in use due to the high cost (Hays, 2001; Kresse et al., 2014).

Fig. 2C and D indicate that drought increases the water applied for irrigation and use of water for MAR, but the water in use for MAR declines quickly as the cost of MAR increases. In drought years, we suppose there is less rainfall during the growing season, but there is still ample water during the wet season to permit recharge. At a recovery efficiency of 60%, the drought increases the cumulative amount of MAR water by approximately 30% at a cost of MAR water of \$20/acre-foot, but the difference in the use of water for MAR between drought and no-drought scenarios is negligible if the cost of MAR is between \$80 and

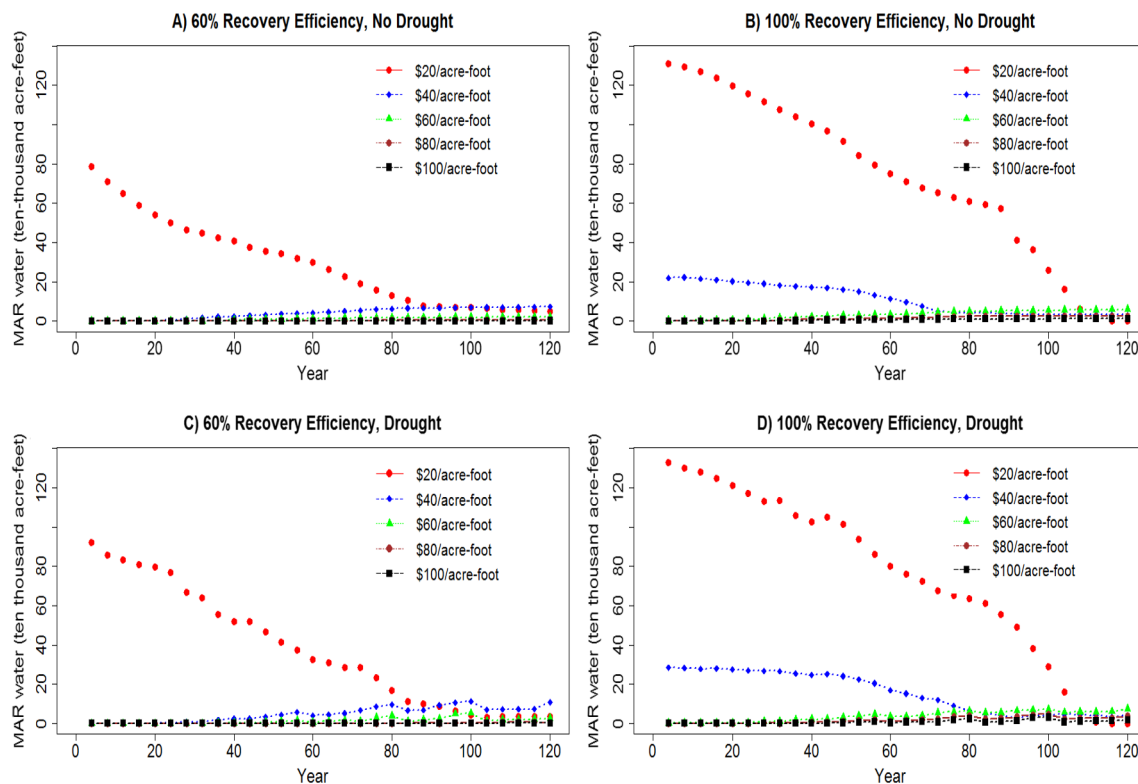


Fig 2. Simulated optimal amount of water for MAR over all sites for the 120-year period (2017–2137) for five cost of MAR water scenarios. Off-farm water cost equals \$200/acre-foot for all the cost scenarios. For (A) and (B), recovery efficiency values equal 60% and 100%, respectively, and all simulated years are non-drought years. For (C) and (D), recovery efficiency values equal 60% and 100%, respectively, and 52 out of the 120-years are drought years.

\$100/acre-foot. Drought has less influence on the water in use for MAR than the recovery efficiency and cost of MAR water.

The optimal use of MAR water over time differs according to the cost of MAR water and the recovery efficiency. At a cost of MAR water less than initial groundwater withdrawal costs, which is approximately \$40/acre-foot for most sites, and a recovery efficiency of 100%, the optimal approach is significant injection early in the time horizon to increase groundwater levels and reduce the pumping costs for the entire time horizon. However, when the cost of MAR water is greater than the initial groundwater withdrawal costs, such as \$60/acre-foot, producers begin to inject when groundwater levels fall to a certain level, and the optimal MAR water use is then set to stabilize the groundwater level and net returns (Fig. 2). The injection of water becomes the cheaper approach to maintain profitability than allowing groundwater levels to continue falling. Table 1 indicates that, for a cost of MAR water above initial groundwater withdrawal costs, producers use less irrigation intensive crops (e.g. non-irrigated soybeans) and no MAR water use for the first half of the time horizon. But in the last half of the time horizon, there are more irrigation intensive crops (e.g. irrigated soybeans), and the use of MAR water.

4.2. Slippage effects

A slippage (or rebound)⁸ effect refers to the increase in groundwater pumping that occurs when more irrigation intensive crops are grown

⁸ Here, we use the term “slippage” rather than “rebound” where slippage refers to increase in irrigated crops acreage due to higher groundwater levels while rebound effect refers to an increase in water application due to higher groundwater levels. The results show that both slippage and rebound effects are happening. The use of MAR water increases irrigated crops in response to lower groundwater pumping costs. There is also movement from less irrigation intensive crops to more irrigation intensive crops that leads to an increase in groundwater withdrawals.

because the cost of irrigation falls due to greater irrigation efficiency or the use of water for MAR. The percentage of slippage refers to the percent increase in groundwater use divided by the use of water for MAR. As an example, Table 1 indicates that the percentage of slippage in the year 2136 at a cost of MAR of \$20/acre-foot is $((114.5 - 102.3) / 35.4) * 100 = 34.5\%$. Fig. 3 indicates that without drought and a cost of MAR water higher than \$90/acre-foot, increased groundwater withdrawal is small and the percentage slippage is less than 30%. At a cost of MAR water of \$20/acre-foot, 34–45% of recharged water is offset through increased groundwater use. Also, when drought is present, which increases the use of water for MAR slightly, the percentage of slippage is higher.

The use of MAR water alone is unlikely to significantly improve the aquifer stock due to the slippage effect unless the cost of MAR water is less than \$20/acre-foot. Contrary to Niswonger et al. (2017) and Scherberg et al. (2014, 2018), when the cost of MAR water is \$40–\$60/acre-foot, the aquifer stock remains nearly the same as the aquifer stock without the use of water for MAR because the percentage of slippage is so high. Additional measures, such as restrictions in land use changes, might therefore be needed for groundwater conservation (Ward and Pulido-Velazquez, 2008).

4.3. Net returns with water from the use of MAR and off-farm surface reservoirs

Fig. 4 shows the response of net returns to a range of off-farm surface water costs for a scenario without the use of water for MAR, and the response of net returns to a range of MAR water costs with no off-farm surface water for three scenarios of MAR recovery efficiency. As costs of water increases, total net returns naturally fall in all scenarios. Off-farm surface storage always provides a higher total net return if the unit price of water from reservoir storage and aquifer storage (MAR) is the same. The higher net returns from surface storage are because the

Table 1

Initial year, half way (year 2077), and final period (year 2136) crop and irrigation choices and net returns with 60% recovery efficiency rate for MAR, no off-farm surface water, and no drought.

Crop and irrigation choices, and net returns	Initial year, 2017	Half way (Year 2077)				Final period (Year 2136)			
		No MAR water ^a	Cost of MAR water (\$/acre-foot)			No MAR water	Cost of MAR water (\$/acre-foot)		
			20	40	60		20	40	60
<i>Crop choice (thousands of acres)</i>									
Irrigated rice	176.2	183.5	240.3	188.2	183.2	200.7	239.5	208.7	200.6
Irrigated corn	110.3	227.2	228.6	241.7	228.1	208.0	229.6	239.1	213.2
Irrigated soybeans & cotton	669.9	494.3	535.2	498.2	501.5	559.8	598.7	573.8	571.2
Nonirrigated soybeans	134.9	165.6	80.0	155.0	167.7	98.6	16.2	61.9	97.4
Fallow	0.0	13.1	0.1	1.1	3.6	17.1	0.1	1.0	1.6
<i>Irrigation choice and aquifer stock (millions of acre-feet)</i>									
Cumulative groundwater use	N/A	51.5	56.1	52.3	51.7	102.3	114.5	105.4	103.1
Cumulative MAR water	N/A	0.0	28.9	1.1	0.2	0.0	35.4	4.9	1.3
Aquifer stock	92.8	76.8	95.0	76.5	76.7	61.7	74.7	61.7	61.6
<i>120-year PV farm net return^b</i>									
	N/A	N/A	N/A	N/A	N/A	6,430	6,529	6,448	6,437

^a The baseline is the scenario that there is no MAR, no off-farm water and no drought.

^b Farm net returns is in millions of 2017 dollars.

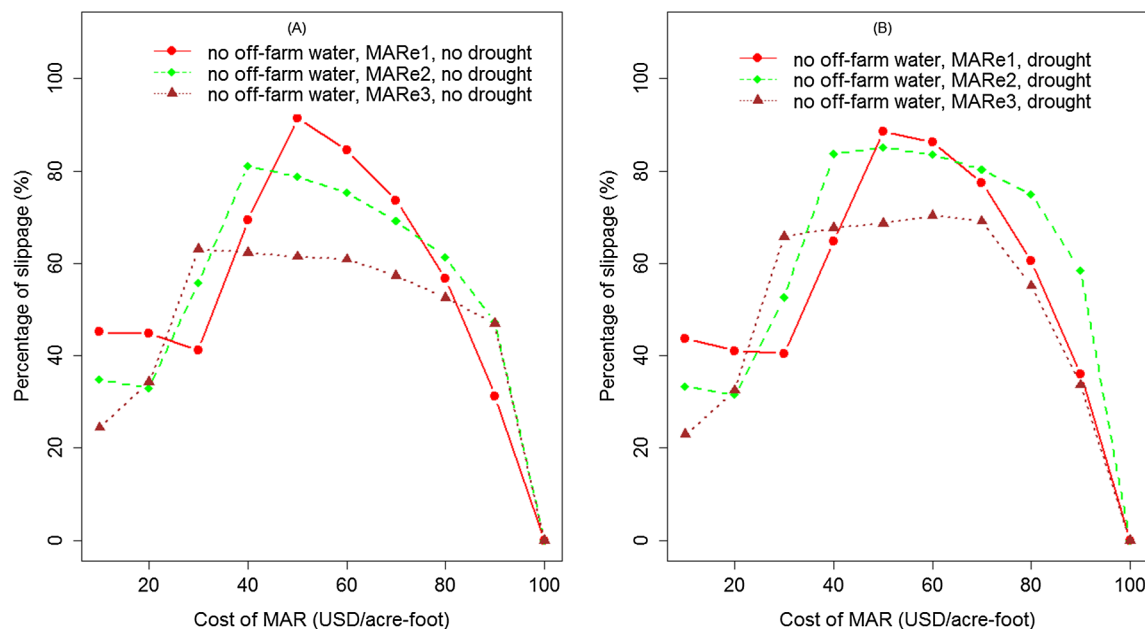


Fig. 3. Percentage of slippage, which is computed as the percentage of injected water offset through increased groundwater use due to land use change into more intensively irrigated land for the entire time horizon. MARE1, MARE2 and MARE3 represent the recovery efficiency of 100%, 80% and 60%, respectively. The potential variation in the cost per acre-foot of MAR water is due to the uncertain infrastructure costs. (A) All years are normal precipitation years. (B) 52 out of 120 years are drought years.

water remains on the surface rather than being pumped up later from the aquifer. The use of water for MAR provides nearly no gain in total net returns if the cost of MAR water is greater than \$40/acre-foot.

4.4. Sensitivity of model outcomes to the cost of off-farm surface water, drought, crop margins, initial depth to groundwater, and the real discount rate

Table 2 indicates the use of water for MAR can slow aquifer depletion if the cost of MAR water is less than \$20 per acre-foot (scenario 20/200 i.e. unit cost of water for MAR of \$20 per acre-foot and a unit cost of water for off-farm surface storage of \$200 per acre-foot) but does not slow aquifer depletion when the cost of MAR water is higher than \$40 per acre-foot. The aquifer declines to 61.7 million acre-feet at the end of time horizon from an initial 92.8 million acre-feet when there is no use of water for MAR water or when the cost of MAR water is higher

than \$40 per acre-foot. Drought intensifies groundwater pumping and increases the use of water for MAR slightly.

Groundwater depletion is less with the conjunctive use of water for MAR and off-farm surface water (scenarios 20/60 – i.e. \$20 per acre-foot of water for MAR and \$60 per acre-foot for off-farm surface water, 40/60, 60/60, 20/80, 40/80, 60/80). For the scenario 60/80, the aquifer stock only declines to about 80 million acre-feet at the end of the time horizon. The cost of off-farm surface water is low enough at \$80 or lower per acre-foot that a significant component of the total irrigation water comes from the surface rather than the ground.

Table 3 shows how the cost of MAR water and the cost of off-farm surface water interact to influence the net returns and aquifer stock relative to a baseline without MAR or off-farm surface water. Cheaper off-farm surface water provides higher net returns and a larger percentage increase in the aquifer stock. Conjunctive use of MAR and off-farm surface water results in more groundwater and higher net returns

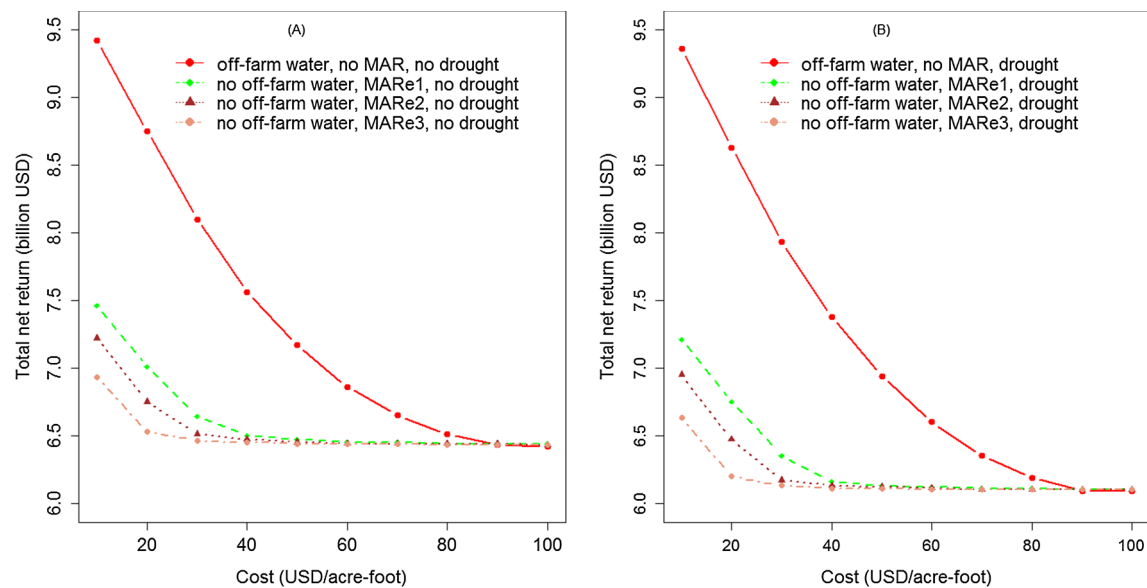


Fig. 4. Total net returns on the landscape in response to the unit cost of water from off-farm surface storage or from MAR using three scenarios of recovery efficiency. MARE1, MARE2 and MARE3 indicate the recovery efficiencies of 100%, 80% and 60%, respectively. (A) All years are normal precipitation years. (B) 52 out of 120-years are drought years.

compared with the use of water for MAR alone. At a cost of MAR water of \$40 per acre-foot, a decrease in the cost of off-farm surface water from \$60 to \$20 per acre-foot makes net returns go from 6.8% above the baseline to 36% above the baseline. For a given cost of off-farm surface water, a decrease in the cost of MAR water has much less influence than the cost of off-farm surface water on net returns and the aquifer stock. At an off-farm surface water cost of \$60 per acre-foot, a decrease in the cost of MAR water from \$60 to \$20 per acre-foot makes net returns go from 6.7% above the baseline to only slight higher at 6.9% above the baseline. However, the more expensive off-farm surface water is, the greater the influence that lower costs of MAR water have on increasing net returns and the aquifer stock above the baseline. The

use of water for MAR buffers net returns against drought, but there is not much buffer for the aquifer stock unless the cost of MAR water is considerably lower than the average groundwater pumping cost.

Table 4 indicates what happens to the use of water for MAR when crop margins double (2CM) or halve (0.5CM) and also what happens when the initial depth to groundwater doubles (2DTW) or halves (0.5DTW). At double the crop margins, the use of water for MAR more than doubles from the baseline to 0.65 and 0.12 million acre-foot for a MAR water cost of \$20 and \$60 per acre-foot, respectively. The significant rise in the use of water for MAR is because groundwater levels fall faster with greater crop water demand due to a shift toward irrigated crops. The groundwater use also increases but does not double,

Table 2

Crop and irrigation choices and net returns with 60% recovery efficiency for selected scenarios of MAR water cost, off-farm surface water storage cost and drought conditions^b.

Scenario considered ^a	Average annual land use choices (thousand acres/year) ^b			Average annual irrigation choices and the final aquifer stock (million acre-foot/year) ^c				Total net return (millions \$)
	Rice	Corn soybeans and cotton	Non-irrigated crops & fallow	MAR	Ground-water pumping	Off-farm surface water	Aquifer stock	
Baseline, no drought ^d	181.9	728.3	174.2	N/A	0.85	N/A	61.7	6430
20/60	248.7	805.9	29.9	0.07	0.58	0.58	116.2	6875
40/60	247.2	801.8	35.5	0.00	0.57	0.59	111.3	6865
60/60	247.0	801.9	35.5	0.00	0.57	0.59	111.3	6864
20/80	236.2	755.0	93.2	0.16	0.78	0.24	90.3	6555
40/80	226.6	742.8	115.0	0.01	0.75	0.23	80.2	6518
60/80	224.4	742.7	117.3	0.00	0.75	0.23	80.3	6514
20/200	220.3	760.3	103.8	0.30	0.95	0.00	74.7	6529
40/200	188.5	747.1	148.8	0.04	0.88	0.00	61.7	6448
60/200	182.1	736.6	165.7	0.01	0.86	0.00	61.6	6437
Baseline, drought ^e	123.6	811.3	149.5	N/A	0.90	N/A	54.0	6090
20/200/drought	170.7	834.7	79.1	0.38	1.02	0.00	72.0	6202
40/200/drought	128.6	836.8	119.1	0.05	0.93	0.00	54.0	6114
60/200/drought	124.0	820.0	140.4	0.01	0.91	0.00	54.0	6101

^a 20/60 is a scenario where the cost of MAR is \$20/acre-foot and the cost of off-farm surface water is \$60/acre-foot, and no drought. 20/200/drought is a scenario where the cost of MAR is \$20/acre-foot and off farm surface water is \$200/acre-foot, and drought is present for 52 out of 120 years.

^b The results show that no land is allocated to on-farm reservoirs when the cost of MAR is less than \$60/acre-foot.

^c The use of water for MAR and from groundwater pumping are annual averages, and aquifer stock is shown for the end of the time horizon (i.e., the end of year 2136).

^d Baseline, no drought is the scenario that there is no MAR, no off-farm surface water and no drought considered.

^e Baseline, drought is the scenario that there is no MAR, no off-farm surface water and drought considered.

Table 3

Influence of the MAR cost of water and the cost of off-farm surface water on the percentage change in net returns and the aquifer stock compared to the baseline.^a

MAR cost (\$/acre-foot)	Off-farm stored water cost (\$/acre-foot)					
	20	40	60	80	200	200, drought
Percentage change in total net returns compared with the baseline (%)						
20	36.0	17.5	6.9	1.9	1.5	1.8
40	36.0	17.5	6.8	1.4	0.3	0.4
60	36.0	17.5	6.7	1.3	0.1	0.2
Percentage change in aquifer stock compared with the baseline (%) ^b						
20	143.1	137.0	88.0	45.9	21.0	33.3
40	143.0	135.9	83.1	29.7	0.0	0.0
60	143.0	135.9	83.0	29.6	-0.2	0.0

^a The baseline is no use of water for MAR. All model runs are for 60% recovery efficiency and no drought.

^b Negative percentage indicates a decrease in the aquifer stock relative to the baseline.

suggesting the use of water for MAR is more profitable than solely mining the groundwater. The use of water for MAR nearly disappears when the crop margins half because there is no reason to supplement groundwater with MAR when minimal groundwater is in use.

At half the initial depth to water, the use of water for MAR increases from 0.30 to 0.37 million acre-feet at a MAR water cost of \$20 per acre-foot and increases from 0.01 to 0.03 million acre-feet at a MAR water cost of \$60 per acre-foot. The use of water for MAR to supplement groundwater is more profitable if the cost of pumping groundwater is less. However, if the initial depth doubles, the use of water for MAR is zero at a cost of \$60 per acre-foot, and only 0.07 million acre-feet of water for MAR annually at a cost of \$20 per acre-foot. The use of MAR to supplement groundwater is less profitable if initial groundwater pumping costs are large. If the real interest rate doubles to 4%, the groundwater pumping remains unchanged, but the use of MAR water declines from 0.3 to 0.09 million acre-feet at a MAR water cost of \$20 per acre-foot. There is less reason to use MAR to support groundwater

Table 4

Influence of crop margins, the depth, and interest rate to groundwater on crop and irrigation choices and net returns with 60% recovery efficiency, no off-farm surface water, and no drought for selected scenarios of MAR water cost.

Scenario considered ^a	Average annual land use choices (1,000 acres/year) ^b			Average annual irrigation choices and the final aquifer stock (million acre-foot) ^c				Total net return (millions \$)
	Rice	Corn soybeans and cotton	Non-irrigated crops & fallow	MAR	Groundwater pumping	Off-farm water	Aquifer stock	
20/200	220.3	760.3	103.8	0.30	0.95	0.00	74.7	6529
60/200	182.1	736.6	165.7	0.01	0.86	0.00	61.6	6437
20/200/2CM	254.6	824.2	5.60	0.65	1.12	0.00	64.4	15,970
60/200/2CM	245.2	819.7	19.5	0.12	1.10	0.00	30.9	15,683
20/200/0.5CM	98.2	602.0	384.2	0.01	0.58	0.00	110.2	2592
60/200/0.5CM	95.2	602.5	386.7	0.00	0.57	0.00	109.9	2592
20/200/2DTW	125.6	674.8	284.1	0.07	0.70	0.00	95.8	5530
60/200/2DTW	116.7	666.1	301.6	0.00	0.68	0.00	92.4	5519
20/200/0.5DTW	240.4	806.9	37.1	0.37	1.05	0.00	65.2	7116
60/200/0.5DTW	204.5	784.0	96.0	0.03	0.95	0.00	48.1	7070
20/200/2R	216.2	768.4	99.8	0.09	0.95	0.00	54.4	3478
60/200/2R	192.4	752.7	138.7	0.02	0.90	0.00	54.4	3462
20/200/0.5R	214.8	766.9	102.7	0.63	0.97	0.00	106.5	10,447
60/200/0.5R	167.5	719.1	197.8	0.01	0.82	0.00	69.3	10,008

^a 20/200 is a scenario where the cost of MAR is \$20/acre-foot and off farm water is \$200/acre-foot, and no drought. 2CM and 0.5CM refers to use of double and half the baseline crop margins. 2DTW and 0.5DTW refers to use of double and half the initial depth to groundwater for all sites. 2R and 0.5R refers to use of double (4%) and half (1%) the real interest rate.

^b The results show that no land is allocated to on-farm reservoirs when the cost of MAR is less than \$60/acre-foot.

^c The use of water for MAR and from groundwater pumping are annual averages, and aquifer stock is shown for the end of the time horizon (the end of 2136).

levels in the future if the present value of future net returns from irrigated production are lower. If the real interest rate halves to 1%, the use of MAR water increases to 0.63 million acre-feet at a low cost of MAR water (\$20 per acre-foot), but remains unchanged at a high cost of MAR water (\$60 per acre-foot). Lower interest rates increase the present value of future returns from irrigated production, and this creates the incentive to sustain the aquifer through greater use of MAR and through a shift from rice to less irrigation intensive corn and soybeans.

4.5. Effect of groundwater conservation policies on the crop and irrigation choices and net returns

Table 5 shows that the pumping cap and tax policies generate a cost (in 2017 US dollars) to society per acre-foot of groundwater conserved that range from \$1.0 to \$35.2. The pumping cap and taxes cause net returns to producers to fall compared to the baseline without the policies, and the cost to society is those losses plus the gain in government revenue if the policy is a tax. As the cost of MAR water increases, the social cost of the pumping cap for groundwater conservation increases from less than \$2 to about \$35 per acre-foot of groundwater conserved. Likewise, the conservation cost of a pumping tax increases with the cost of MAR water, from approximately \$1–\$22 per acre-foot of groundwater conserved. Since a lower cost of MAR water reduces the groundwater conservation cost of cap and tax policies, MAR and conservation policies appear to be complements for conservation. Also, a recovery efficiency higher than 60% makes the conservation cost even lower. Conservation policies increase the aquifer stock less when the cost of MAR water is low, but the social cost of the policies are also lower. The pumping tax is a more cost-effective approach to conserve groundwater compared to the pumping cap.

5. Conclusion

Our results on the optimal economic use of water for MAR contrast with the results from hydrologic models where land use is fixed (Niswonger et al., 2017; Scherberg et al., 2014, 2018). At the likely cost of MAR water for irrigation in Eastern Arkansas, which is at least \$40 per acre-foot (Falconer and Johnson, 2017), the use of water for MAR is unlikely to reduce groundwater overdraft. Our model indicates that the

Table 5Selected land use and economic outcomes of selected MAR water costs and water conservation policies with 60% recovery efficiency, 2017–2136.^a

Cost of MAR water (\$/acre-foot)	Policy	Average annual land use choices (1000 acres/year)			Average annual irrigation choices and the final aquifer stock (million acre-foot) ^a		Economic outcomes (million dollars)		Social cost of groundwater conservation (\$/acre-foot)
		Rice	Corn, soybeans & cotton	Non-irrigated crops & fallow	MAR	Groundwater pumping	Policy cost ^b	Total net returns	
20	75% cap ^c	220.2	758.3	105.9	0.41	0.95	18.3	6498	1.9
20	10% tax ^d	215.6	757.9	111.0	0.40	0.95	12.1	6415	1.0
40	66% cap	180.2	707.4	196.8	0.15	0.82	264.9	6284	29.2
40	55% tax	145.5	680.1	258.8	0.01	0.73	140.2	5886	16.6
60	66% cap	171.1	649.6	263.8	0.05	0.76	323.3	6206	35.2
60	60% tax	138.4	666.5	279.5	0.001	0.71	257.9	5802	21.7

^a The use of water for MAR and from groundwater pumping are annual averages is shown for the end of the time horizon.^b Policy cost is the sum of the change in net returns and tax revenue without and with the policy.^c The pumping cap at a MAR water cost of \$20/acre-foot is set equal to 75% of the initial pumping rate. Groundwater pumping in excess of the cap can occur if MAR replaces in full the excess groundwater pumping. At this pumping cap, the aquifer stock is 84.5 million acre-feet compared with 74.7 million acre-feet at a MAR water cost of 20/acre-foot and no pumping cap. The pumping cap at MAR water cost of \$40 and \$60/acre-foot is set to achieve a level of groundwater conservation similar to the 75% pumping cap at a MAR water cost of \$20/acre-foot.^d The pumping tax is set to achieve a level of groundwater conservation similar to the 75% pumping cap at a MAR water cost of \$20/acre-foot.

use of water for MAR has a moderate role in the alleviation of groundwater overdraft at a cost of \$40 per acre-foot due to minimal injection and the slippage effect. There is evidence that producers would shift to more irrigation intensive crops with the availability of MAR water, and groundwater pumping could increase. A more effective approach for reducing the groundwater overdraft is the conjunctive use of MAR water and surface water storage. This is only effective though if the cost of the surface water deliveries are less than the \$100/acre-foot. Groundwater conservation policies such as the use of a cap or fee on groundwater extraction are more cost-effective with the use of water for MAR.

If the cost MAR water is much lower than the average groundwater pumping cost, then MAR should begin early in the time horizon to lower groundwater pumping costs over the entire study period. Drought slightly increases the use of water for MAR, but drought is unlikely to make MAR economically feasible. Higher irrigation demand by doubling crop margins more than doubles the use of MAR water to supplement the groundwater, but halving the crop margins nearly eliminates the use of water for MAR even at the lowest cost of MAR water. The use of water for MAR is thus heavily dependent on the anticipated irrigation demand of crops. Also, regions with large depths to the aquifer are unlikely to use MAR water to supplement groundwater because the cost of pumping the water back out of the aquifer is high. A lower real discount rate encourages aquifer conservation and MAR water use while a higher real discount rate does the opposite.

Water policy makers continue the search for strategies to allow producers to maximize net returns and sustain the groundwater resource. Greater irrigation efficiency can increase water use through the slippage effect and not necessarily conserve groundwater (Grafton et al., 2018), and conjunctive use strategies such as the use of surface water reservoirs should also proceed with caution since the slippage effect can also occur (Kovacs and Durand-Morat, 2017). Our study finds that unless the cost of MAR water is substantially less than the average groundwater pumping cost or the cost of water from surface storage is about the same or less than the average groundwater pumping cost, then the slippage effect is large.

We suppose ample water for MAR is available in Eastern Arkansas, but periods of extreme drought might limit the water available for MAR and surface reservoirs. If the use of water for MAR is known not to be possible in some years, this would increase MAR when precipitation is abundant. Also, for a shorter time horizon, a model could allow for deficit irrigation rather than assume producers switch to new irrigation practices or less water intensive crops. Another extension to the model is to change the number of sites in the study area, which would be equivalent to decreasing or increasing the proximity of the wells, and examine what this does to the well pumping of the surrounding sites.

The hydrological component of our model is simple, particularly in the assumption that there are no lateral flows between sites, to allow for computationally tractable optimization. An economic model coupled with a more sophisticated hydrologic model such as MODFLOW would better account for the complexity of groundwater flows. Also, our model overlooks the potential effects of climate change on aquifer recharge (Pulido-Velazquez et al., 2015, 2018; Zhang et al., 2016; Meixner et al., 2016; Gemitzi et al., 2017; Smerdon, 2017) and the assessment of conjunctive use strategies (Pulido-Velazquez et al., 2011, 2008; Escrivá-Bou et al., 2017). Since drought will change in the future due to climate change, future studies could incorporate a statistical approach to generate climate scenarios to evaluate the impact of a potential shift in the intensity and frequency of drought on the economics of MAR (Fatichi et al. 2011; Collados-Lara et al. 2018).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2019.124220>.

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