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RESEARCH ARTICLE

Optimal Management of Irrigation Water from Aquifer and Surface sources

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Abstract

We explore the economic merits of on-farm water storage with tailwater recovery systems to reduce aquifer depletion in a region with expanding irrigated acreage and substantial off-season precipitation. Gains are substantial on a broad scale and long planning horizon, including more than $4 billion in producer surplus, 5 million acre-feet of conserved groundwater, and land capitalization of $24 per acre. Sensitivity analyses provide insights with respect to the impact of discount rates, rainfed returns, return flows, and aquifer recharge rates. Results can inform stakeholders about the optimal allocation of funds directed at agricultural practice adoption and agricultural water investments.

Keywords: Alluvial aquifer; on-farm water storage; optimal drawdown; renewable resource; user cost

JEL classifications: Q15; Q24; Q25; Q28

1. Introduction

The Mississippi River Valley Alluvial Aquifer (MRVAA) underlies a large area with diverse groundwater conditions in terms of groundwater availability. In areas where groundwater demand for irrigation exceeds its natural rates of recharge, the MRVAA is depleting at unsustainable rates (Quintana-Ashwell et al., 2020; Yasarer et al., 2020). Untimely aquifer depletion imposes economic losses that are not immediately evident to groundwater-dependent producers (Quintana-Ashwell, Peterson, and Hendricks, 2018). This paper focuses on an area in the Mississippi side of the Lower Mississippi River Basin (LMRB) where relatively abundant groundwater makes development of infrastructure to capture and store pluvial and irrigation runoff not immediately necessary, or financially viable, for private farmers. Part of the economic cost of temporal misallocation of groundwater is that excessive, or relatively less valuable, use in the present reduces the ability of producers to apply it in the future when it is more needed or valuable. Another important cost relating temporal allocation and the stock of groundwater is that the gains achievable with optimal management of the resource diminish with the stock available. Most importantly, continued depletion of the MRVAA may result in higher producer exposure to the increasing risks associated with climate change which may come in the form of more severe and frequent droughts (MacDonald, 2010; Tran, Kovacs, and Wallander, 2020)—which translate to higher likelihood of steep financial losses for farmers.

Limited global freshwater supplies, exacerbated by depleting aquifers, add pressure to expand agricultural productivity and irrigated acreage in regions with relatively rich freshwater resources, such as the Delta region in Mississippi (Elliott et al., 2014). Despite average annual rainfall of 50–60 in., as much as three-fourths of the precipitation in the Delta occurs outside the critical stages of the growing season (University of Washington, 2010). This problem is compounded by

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the high spatial variability and intensity of precipitation which results in intense pluvial runoff in a field and near-drought conditions in a neighboring field. Surface water from rivers and streams may be available for irrigation but concerns remain regarding quality and quantity reliability—excess during flood and scarcity during droughts. The result is the rapid propagation of groundwater-based irrigation to minimize risks and maximize yields. Newly permitted acreage for irrigation in the Delta increased by nearly 220,000 ac. between calendar years 2012 and 2020.[1]

On-farm water storage with tailwater recovery facilities (OFWS) emerge as a technical solution capable of reducing irrigator dependence on groundwater stocks by capturing and storing pluvial and irrigation runoffs that can be reapplied in irrigation events. In this paper, OFWS is modeled as an optimal control problem in which the water table elevation of the aquifer is the state variable and the amount of irrigation water applied from ground and surface water sources are the control variables. We find that long-term OFWS preserves 60–70 ft. of aquifer saturated thickness compared to the baseline without OFWS and approximately 47 ft. more of aquifer saturated thickness than the scenario in which OFWS levels are endogenously and irreversibly determined for every season. We also find that short-term (less than 50-year horizon) practice comparisons obscure the benefits of OFWS which become evident in longer planning horizons.

Large portions of the literature on groundwater management focuses on the common pool property of aquifers in arid and semi-arid areas (Allen and Gisser, 1984; Brill and Burness, 1994; Brozović, Sunding, and Zilberman, 2010; Burness and Brill, 2001; Feinerman and Knapp, 1983; Gisser, 1983; Gisser and Sanchez, 1980; Kim et al., 1989; Negri, 1989; Pfeiffer and Lin, 2012; Provencher and Burt, 1994; Quintana-Ashwell and Peterson, 2016; and Quintana-Ashwell, Peterson, and Hendricks, 2018). The focus in that line of research is on comparing optimal groundwater extraction paths to those occurring under competitive or nonintervention paths to determine whether gains may be achieved by active resource management intervention (Quintana-Ashwell, Peterson, & Hendricks, 2018). The formulation in the seminal work by Gisser and Sanchez (Gisser and Sanchez, 1980) had stringent assumptions that yielded results known as the "Gisser and Sanchez Effect" (GSE) that suggested focus should shift away from optimal extraction paths into allocation to higher value uses to achieve "second-best" allocations (Gisser and Sanchez, 1980). Over time, it became clear that GSE vanishes as the stringent assumptions are relaxed revealing substantial gains that may be achieved with management interventions (Koundouri, 2004). In this paper, we examine the optimal extraction paths and compare it to a nonintervention competitive baseline, but we relax the bottomless aquifer assumption in the original literature by imposing a relative lift pumping cost formulation that prevents pumping beyond the bottom of the aquifer. Another important departure from that literature is that our work applies to a humid region in which water availability is not necessarily the limiting input for irrigated agriculture, but land is—i.e., current supplies can support irrigation of all cropland at the moment but not in a sustainable manner.

This work is also related to research that studies the conjunctive use of groundwater and surface water, most of which focused on the interactions between aquifers with rivers and streams (Burt et al., 1964; Chakravorty and Umetsu, 2003; Knapp and Olson, 1995; Knapp et al., 2003; Mulligan et al., 2014; Pulido-Velazquez et al., 2008; Tsur, 1990); and cases in which high-salinity water sources act as a backstop alternative (Duarte et al., 2010; Koundouri and Christou, 2006; Krulce, Roumasset, and Wilson, 1997; Pongkijvorasin et al., 2010; Roumasset and Wada, 2010).

The practice of capturing and reapplying surface water is relatively new in the Delta of Mississippi (Czarnecki, Omer, and Dyer, 2017) although farmers in the Grand Prairie of Arkansas have been developing tailwater recovery and storage structures over several decades (Yaeger et al., 2018). Indeed, there is a growing literature on the economics of OFWS in Arkansas (Kovacs and Mancini, 2017; Popp et al., 2003; Wailes et al., 2003; Yaeger et al.,

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2018) and as a water quality preservation practice (Karki, Tagert, and Paz, 2018; Omer et al., 2019). Existing OFWS studies in the Mississippi Delta region are based on site data and time horizons of 30 years or less (Falconer, Lewis, and Krutz, 2015; Falconer, Tewari, and Krutz, 2017; Omer et al., 2019). Longer term benefits of OFWS compound because at the end of the 30-year useful life, these facilities retain extremely high recovery value. These studies are not concerned with optimal extraction paths and they present conclusions based on farm-level costs and returns over the lifespan of the structure without interactions with the aquifer. They tend to find that OFWS is not the most economical way of achieving water quantity or quality goals in Mississippi because of the costs of retiring land from production and building the required infrastructure (Falconer, Lewis, and Krutz, 2015; Falconer, Tewari, and Krutz, 2017; Omer et al., 2019).

A number of studies on OFWS explore the merits of these systems for the Arkansas side of the Mississippi Delta. There, alluvial aquifer depletion has been more acute that in Mississippi, which makes the benefits of OFWS more evident over shorter planning horizons. In fact, several studies find that OFWS is a profitable option when there is limited water availability (Kovacs and Mancini, 2017; Popp et al., 2003; Wailes et al., 2003), adequate cost-sharing incentives are available (Kovacs et al., 2014; Popp et al., 2003), groundwater use is taxed (Kovacs et al., 2014), or a portion of the stock of water in the OFWS recharges the aquifer (Kovacs et al., 2015)—the planning horizons are typically 30 years in these studies as well.

The Delta in Mississippi may not be in the same circumstances as its neighbors to the west, but our area of study is traversing a similar path towards that critical situation and would be interested in getting ahead of that curve in terms of adopting groundwater-conserving practices such as OFWS. Our work examines the optimal extraction over a prolonged period of time (hundreds of years) to assess long-term sustainability and focuses in a geographic area that has experienced a critical depletion in the groundwater stocks. The optimal control formulation provides insight regarding the sustainability of the aquifer by alleviating the pressure on extraction and by aiding in the recharge via additional return flows.

2. Materials and Methods

We first develop a stylized continuous-time dynamic analytical model of groundwater use with irreversible surface water storage capacity. The model in this section is simplified to develop an intuition about what drives the outcomes. In the next section, we present numerical solutions for an area of acute aquifer depletion in Sunflower County, MS.

2.1. The Model

The analytical model assumes one productive activity: irrigated agriculture. This is a palatable assumption for the Delta because the agricultural sector pumps only from the alluvial aquifer and deeper wells are not currently permitted for agricultural production. Considering the (inverse) demand for irrigation water, *P(X)*, the total benefits from applying *w* acre-feet of groundwater and *s* acre-feet of OFWS water for irrigation is the area under the inverse demand curve up to that point: $B(w_t, s_t) = \int_0^{w+s} P(X)dX, \frac{\partial \mathrm{B}}{\partial w}(w, s) \geq 0, \frac{\partial \mathrm{B}}{\partial s}(w, s) \geq 0$, which allows yield plateaus but no waterlogging losses; and $\frac{\partial^2 \mathrm{B}}{\partial w^2}(w, s) \leq 0, \frac{\partial^2 \mathrm{B}}{\partial s^2}(w, s) \leq 0, \frac{\partial^2 \mathrm{B}}{\partial w \partial s}(w, s) \leq 0$. The use of the demand curve simplifies the analysis by employing the implicit crop mix and rotations by farmers in the area and their relative value. The simplest formulation that satisfies these properties (with waterlogging losses) is a linear (inverse) demand function:

$$P(u) = \beta_1 - \beta_2 u; \tag{1}$$

which can be easily calculated when there is data on the elasticity of groundwater demand with respect to pumping cost.

2.1.1. Groundwater Pumping Cost

The marginal cost of pumping groundwater, $C_g(\cdot)$, depends on the lift distance and the aquifer saturated thickness, both of which are a function of the aquifer water table elevation (h). In this single agent model, a representative set of characteristics, summarized in Table 2, is estimated. The key aquifer parameters to estimate average groundwater pumping costs are surface water elevation (S_L), water table elevation (h_t) and well drawdown (d). For each period, the average pumping cost is calculated using a relative lift formulation (Brill and Burness, 1994; Burness and Brill, 2001; Quintana Ashwell and Peterson, 2016; Quintana Ashwell, Peterson, and Hendricks, 2018; Sloggett and Mapp, 1984):

$$C_g(h_t) = \frac{\theta}{Y_t} \times \frac{S_L - h_t}{S_L - h_0}; \tag{2}$$

where θ is the cost of pumping for one hour at initial lift and Y_t is the well yield in acre-ft per hour. Well yield depends on aquifer saturated thickness and is calculated following Burness and Brill (2001) adaptation of Sloggett and Mapp (1984) as $Y_t = 2Q_0 d[h_t - h_b - d/2]$; where d is well drawdown, h_b is the elevation of the aquifer bottom, and Q_0 is a unit-less well coefficient that depends on aquifer permeability, well radius and the radius of the cone of depression. For the simulation, we employ an average drawdown of 20 ft. and calibrate the coefficient Q_0 residually from a well for which we know the yield and approximate saturated thickness.

This formulation captures the temporal externality of groundwater pumping in two ways. First, it updates the average pumping cost based on updated water table elevations that evolve according to equation (3). Secondly, the cost of pumping groundwater increases nonlinearly as the aquifer depletes. Furthermore, the hydrologic model represented in equation (3) captures the common property externality updating the water table elevation uniformly across the county.

As the aquifer depletes (h decreases), the cost of extracting groundwater increases rapidly, $C_g{}'(h) < 0, C_g{}''(h) \geq 0$. To avoid the bottomless aquifer problem that drives the GSE, the cost of pumping becomes uneconomical before the water table reaches the aquifer bottom: $\lim_{h \to (h_b + 0.5d)} C_g(h) = \infty$. The marginal pumping cost in equation (2) satisfies these properties.

2.1.2. State of the Aquifer

The elevation of the aquifer water table depends on the net rate of recharge, r, how much groundwater is pumped, and what portion of the water applied for irrigation becomes return flows, α. Consequently, the aquifer water table elevation changes over time according to:

$$\dot{h}(t) = \frac{r - (1-\alpha)w_t + \alpha s_t}{A_s}, \tag{3}$$

where A_s is a measure of how much groundwater the aquifer can hold and is calculated as the number of acres that overlay the aquifer times specific yield. The water table elevation is always above the bottom of the aquifer, $h_t > h_b \forall t$, and the initial state is defined by the starting water table elevation, h_0.

The cost of pumping from OFWS, $C_s(s_t) = C_s s_t$, is a linear function of the volume s_t applied from OFWS. This linear cost is plausible because the re-lift elevation from the tailwater recovery facility to the reservoir and any frictional losses from pumping from the reservoir to the top of the field are constant over time. The other cost associated with using water from OFWS is the capital cost of building and keeping the required infrastructure as well as the opportunity cost of the land used for the reservoir and ditches that could otherwise have been farmed. The capital and opportunity cost of the OFWS facility are annualized with the parameter γ on a per acre basis and is multiplied by the acreage required for OFWS in a given year. To avoid the complexity of

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decommissioning costs, we further assume the acreage devoted to OFWS is irreversible: $FR_t \geq FR_{t-1}$, where FR_t is the acreage required for the system.

Because land is the limiting factor, an acreage constraint is required. The irrigated acreage is calculated as $A_t = (1-\alpha)\varepsilon(w_t+s_t)/C_R$, where ε is the average irrigation application efficiency and C_R is the weighted average irrigation water requirement for the crop mix. The acreage devoted for OFWS is calculated as the minimum acreage required for the surface water in a given season: $FR_t \geq \Upsilon s_t$. The rain-fed acreage is calculated residually by subtracting the other land uses from the total cropland available, AG_t: $RF_t \leq AG_t - a_t - FR_t$.

2.1.3. Planning Problem

The optimal control problem consists of choosing the pumping decisions that maximize the net present value of the stream of benefits from the conjunctive management of groundwater and OFWS (NPV) over the life of the aquifer:

$$\text{NPV} = \int_0^\infty e^{-\delta t}\left[B(w_t, s_t) + \rho RF_t - c_g(h_t)w_t - C_s s_t - \gamma FR_t\right]dt,$$

where δ is the discount rate, ρ is the average returns to rainfed acres, and each period is subject to equation (3), $w_t \geq 0, s_t \geq 0, FR_t \geq FR_{t-1} \geq 0$, and $RF_t \geq 0$.

The current value Hamiltonian[2] and Lagrangean incorporating the constraints are, respectively,

$$H = B(w+s) - C_g(h)w - C_s s - \gamma FR + \rho RF + \psi\left(\frac{r-(1-\alpha)w+\alpha s}{A_s}\right), \tag{4}$$

$$L = H + \lambda_1(FR - \Upsilon s) + \lambda_2(AG - A - FR - RF); \tag{5}$$

where ψ is the costate variable while $\lambda_1, \lambda_2 \geq 0$ are the Lagrangean multipliers associated with the acreage constraints.

The necessary conditions are

$$\frac{\partial L}{\partial w} = \beta_1 - \beta_2(w+s) - C_g(h) - \psi\frac{(1-\alpha)}{A_s} - \lambda_2\frac{(1-\alpha)\epsilon}{C_R} = 0; \tag{6}$$

$$\frac{\partial L}{\partial s} = \beta_1 - \beta_2(w+s) - C_s + \psi\left(\frac{\alpha}{A_s}\right) - \lambda_1\Upsilon - \lambda_2\frac{(1-\alpha)\epsilon}{C_R} \leq 0, s \geq 0, s\left[\frac{\partial L}{\partial s}\right] = 0; \tag{7}$$

$$\frac{\partial L}{\partial FR} = -\gamma + \lambda_1 - \lambda_2 \leq 0, FR \geq 0, FR\left[\frac{\partial L}{\partial FR}\right] = 0; \tag{8}$$

$$\frac{\partial L}{\partial RF} = \rho - \lambda_2 \leq 0, RF \geq 0, RF\left[\frac{\partial L}{\partial RF}\right] = 0; \tag{9}$$

$$\frac{\partial L}{\partial \lambda_1} = FR - \Upsilon s \geq 0, \lambda_1 \geq 0, \lambda_1\left[\frac{\partial L}{\partial \lambda_1}\right] = 0; \tag{10}$$

$$\frac{\partial L}{\partial \lambda_2} = AG - RF - FR - \frac{1-\alpha}{C_R}\epsilon(w+s) \geq 0, \lambda_2 \geq 0, \lambda_2\left[\frac{\partial L}{\partial \lambda_2}\right] = 0; \tag{11}$$

$$\dot{\psi} - \delta\psi = -\left[\frac{\partial L}{\partial \lambda_2}\right] = C_g'(h)w; \text{and} \tag{12}$$

[2] t subscripts omitted hereafter.

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$$\dot{h} = \frac{\partial L}{\partial \psi} = \frac{r - (1-\alpha)w + \alpha s}{A_s}. \tag{13}$$

This system is solved numerically in Section 3 with estimated parameters for Sunflower County, MS. However, it is useful to draw some intuition from the optimality conditions.

In this simplified model, from equation (9), rainfed agriculture vanishes if rainfed returns are less than the average returns from agricultural land in other uses: $\rho < \lambda_2$. This also implies that equation (11) holds with equality when expected returns from rainfed agriculture are positive ($\lambda_2 \geq \rho > 0$), indicating fallow land is suboptimal.[3]

From the groundwater extraction optimality condition (6), we see the scarcity value of stored groundwater for each period, ψ, depends on the value marginal product of irrigation water at the optimal application level, $P(w^{*}+s^{*})$; the marginal cost of pumping groundwater, $C_g(h)$; and the marginal cost of irrigable cropland, $\lambda_2(1-\alpha)\varepsilon/C_R$:

$$\frac{\psi(1-\alpha)}{A_s} = \beta_1 - \beta_2(w^* + s^*) - C_g(h) - \lambda_2 \frac{(1-\alpha)\epsilon}{C_R}. \tag{14}$$

Notice that it also depends on the mainly hydrologic characteristic of the area overlying the aquifer associated with aquifer recharge. Recall that A_S captures, in essence, the ability of the aquifer to store water and α captures how much of the water applied to irrigation makes its way back to the aquifer.

The next important intuition is on the optimality of using water from OFWS. The first useful comparison is to determine which situation would prevent any optimal use of OFWS water, $s = 0$. A comparison of conditions (14) and (7) indicates that no water from OFWS should be used when the marginal cost of pumping from OFWS and the annualized capital and opportunity cost of the infrastructure, net of the return flow benefit to the aquifer, is greater than the marginal net benefit from irrigation net of the positive effect of OFWS use on groundwater pumping cost:

$$(1-\alpha)(C_s + \lambda_1 \Upsilon) > \beta_1 - \beta_2(w^* + s^*) - \alpha C_g(h) - \lambda_2 \frac{(1-\alpha)\epsilon}{C_R}. \tag{15}$$

Conversely, when water from OFWS is optimally used, the relation (15) becomes an equation.

Even if OFWS is suboptimal in early periods, it may become an optimal tool if the pumping and opportunity costs from OFWS decrease, the marginal benefits from irrigation increase, or the cost of groundwater pumping increase sufficiently over time. Consequently, the planning horizon and the salvage value of OFWS infrastructure are of the utmost importance in calculating the annualized cost γ. In short, if the scarcity value of groundwater, ψ, grows sufficiently, it may induce the expansion of OFWS capacity. From condition (12), it is clear that the scarcity value of the aquifer does not diminish over time.

For the case study, we adapt the problem to discrete time and solve it using the constrained non-linear solver *fmincon* with the interior point algorithm in *MatLab R2020a*.

2.2. Area of Study

Sunflower County, MS, is in the center of the Delta area of Mississippi (red contour in Figure 1). It fully overlies an acute depression of the MRVAA water table[4] that has drawn concern from producers as well as federal and state agencies. Because of concerns about MRVAA depletion, Mississippi Governor Phil Bryant established the Governor's Delta Sustainable Water

[3]Since the model assumes typical crop choices in C_R, this is not entirely precise because if the rotations include some fallowing, those acres would be accounted for as part of irrigated land.

[4]The area is colloquially referred to as the "cone of depression;" a potentially confusing misnomer as a cone of depression occurs at any well actively pumping.

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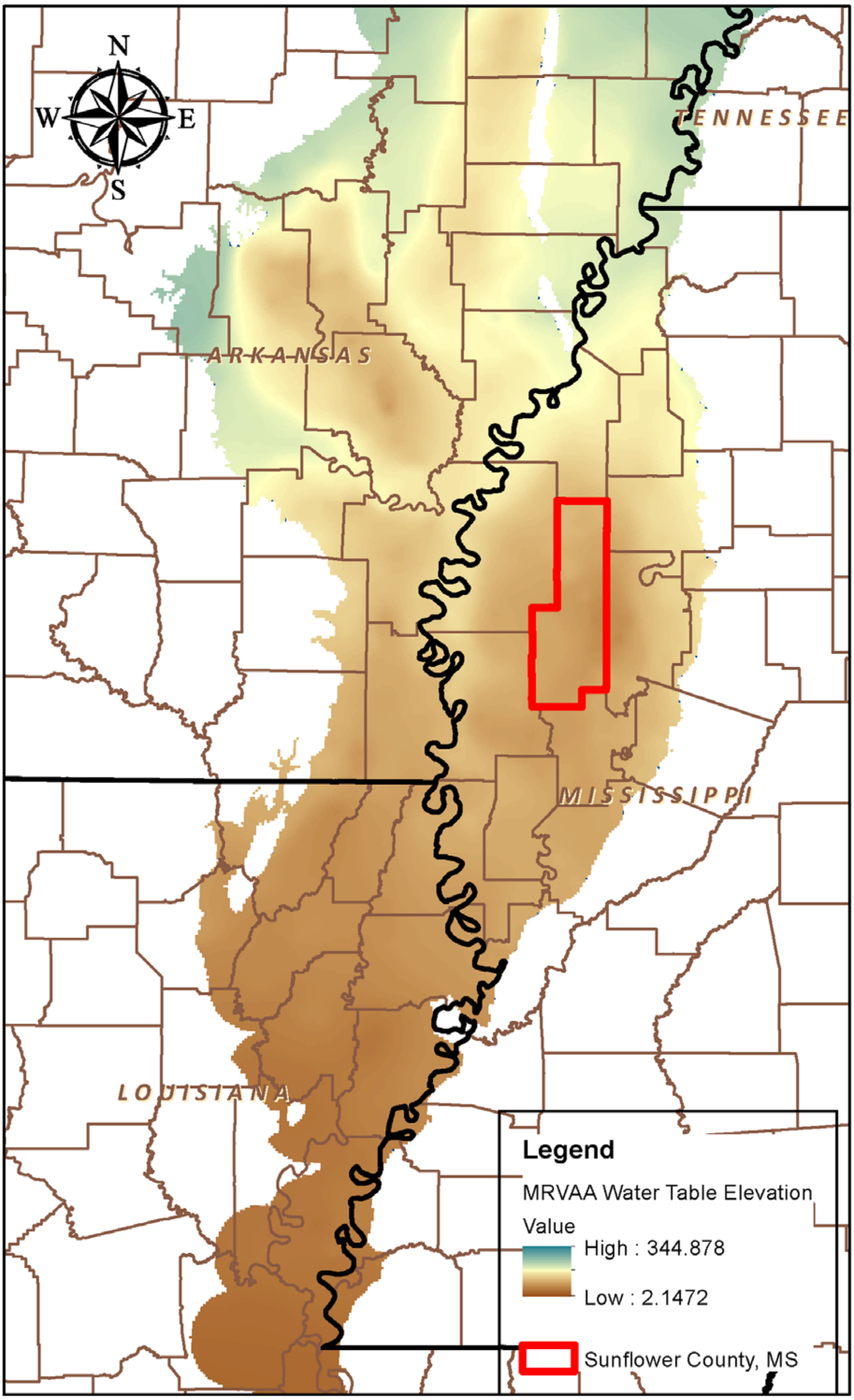

Figure 1. Sunflower county, MS, overlies an area of acutely depressed groundwater levels. OFWS implementation has been concentrated in this area (Omer et al., 2019).

Table 1. Annualized investment and opportunity cost for on-farm water storage with tailwater recovery system

	Initial Cost	Life Years	Salvage Value	Annual Cost
Excavation	$33,000	20	90%	$203
Levees	$45,000	20	90%	$276
Pumping plant	$42,000	20	10%	$2,321
Underground pipe	$9,240	20	80%	$113
Flowmeter stand	$1,950	20	85%	$18
Land				$1,308
Total				$4,239
Total per acre				$353

Source: Falconer et al. (2017) and USDA-NASS.

Resources Task Force on November of 2011 to ensure the future sustainability of water resources in the Delta (Bryant, 2014).

The adoption of OFWS has been focused in Sunflower and bordering counties (Omer et al., 2019). The row-crop agriculture in the county is widely representative of the Delta. Consequently, the area is ideal for a representative agent type of model such as this, as it is big enough to draw conclusions about the aquifer but small enough that a single-cell aquifer model is capable of capturing the most important dynamics (Brozović, Sunding, and Zilberman, 2010).

2.3. Data and Parameters

2.3.1. On-Farm Water Storage with Tailwater Recovery Systems (OFWS)

The specific characteristics of OFWS facilities are as unique as the sites they are built on. However, the base design considered in USDA NRCS programs considers an engineered micro-catchment area that includes earth moving and infrastructure for the entire base acreage capable of providing 100% of the irrigation needs of 50% of the acres in the catchment, 8–9 out of 10 years (Paul Rodrigue, USDA NRCS, personal communications). We assume the entire micro-catchment area is treated to calculate the OFWS capital recovery cost for the representative agent. Alternative layouts based on site characteristics may leverage existing features that could result in lower OFWS capital costs than stipulated here.

The basic OFWS design applies to 172 hypothetical acres, 160 ac. of which are the catchment and tillable land and 12 ac. are used for the tailwater recovery ditch, reservoir, and required infrastructure. Tailwater recovery facilities are the key components to capture pluvial and irrigation runoff for reuse. Reservoirs by themselves are considered insufficient by USDA NRCS to capture enough precipitation to sustain irrigation because precipitation is considered only sufficient to compensate for evaporative losses in the reservoir. This observation from NRCS allows us to omit any further modeling of the evaporative losses and precipitation gains in reservoir water stock—which could be an interesting extension of the model.

Table 1 details the annual capital recovery cost of the investment required for OFWS. The two pumping plants are the most expensive components at $42,000. One plant is required to lift from the tailwater ditch into the reservoir and another to apply water from the reservoir on the fields. The opportunity cost of the additional land needed for OFWS is $109 per acre which is the average rental rate for non-irrigated land in Sunflower County, MS (USDA-NASS, 2020).

The minimum amount of land required to provide s acre-feet of OFWS is determined by the ratio of a 12 ac. footprint for 80 ac.-ft. of applicable water capacity, or $OFWS = 12/80s$,

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in terms of the optimization model: $\Upsilon = 3/20$. The annualized capital recovery cost and the opportunity cost of the land devoted to the reservoir and tailwater recovery system for OFWS, $\gamma = 244 + 109 = 353$—see Tables 1 and 2. The energy cost of applying an acre-foot of water from the OFWS on the fields, EC, is calculated from:

$$\mathrm{EC} = \frac{Z}{\mathrm{NPS}} \times \mathrm{Head} \times P_e \times 12,$$

where $Z = 0.11345$ is a conversion factor from gallons per minute (GPM) to horsepower-hour per acre-inch per feet of head; $\mathrm{NPS} = 18.5 \times 0.75 \times 0.95$ is the Nebraska Pumping Standard (Engine power output in hp-hr-gal × pump efficiency × gear-head efficiency); Head is the dynamic head (11.278 ft. relift plus 3 ft. for frictional losses are converted to additional head); and $P_e = 2.55$ is the price of off-road Diesel obtained from the U.S. Energy Information Administration.

2.3.2. Demand for Irrigation Water

A recent publication from researchers at the U.S. Geological Survey (USGS) estimates the cost elasticity of groundwater for irrigation at −0.13 (Alhassan et al., 2020). The data for that article are at the county level with an aggregate quantity demanded for Sunflower County, MS, of 271,909 acre-ft in 2015 and an average pumping cost of \$16.28 per acre-ft. This estimate from USGS is used to calibrate a linear demand curve for groundwater combined with county-level estimates of groundwater use for irrigation (USDA-NASS, 2020) and pumping costs calculated based on USGS data—consistent with a quadratic profit function. The slope of the water demand function ($Q(P)$) is obtained from the elasticity estimate as $b = \mathrm{E} \times \mathrm{Q_{obs}}/\mathrm{P_{obs}}$ and the intercept as $a = Q_{\mathrm{obs}} - bP_{\mathrm{obs}}$, which is converted to an inverse demand function ($P(Q) = \frac{a}{b} - \frac{1}{b}Q = \beta_1 - \beta_2 Q$).

The most relevant parameter values in the model are summarized in Table 2.

Elevations in Sunflower County range from 100 feet above mean sea level (fsl; North American Vertical Datum 1988, NAVD) in the south to 145 fsl in the north (FEMA, 2010) and average surface elevation of 118 fsl (McGuire et al., 2019). Initial aquifer parameters are averaged from publicly available USGS potentiometric maps (McGuire et al., 2019). Tran et al. (2020) assumes 29% return flows from irrigation water applications in nearby areas in Arkansas but we employ a more conservative 10% return flow from irrigation.

Acreage for cropland, irrigated land, and crop shares are calculated with data obtained from USDA-NASS (2020). Crop irrigation water requirements are obtained from Massey et al. (2017). Average irrigation water application efficiency is estimated based on Bryant et al. (2021) considering that furrow irrigation is predominant in the area.

The sum of the stream of farm profits is discounted to the Net Present Value (NPV) applying a 2% discounting rate as in Tran et al. (2020). Average returns for rainfed agriculture are estimated based on Mississippi State University Extension Service.[5]

Although some producers who employ OFWS tell us in private conversation that they see a yield effect from using the surface water, we could not find clear evidence of this effect in the literature. Consequently, we assume the seasonal marginal benefits from irrigation are independent of the water source and depend only on how much irrigation water has been applied to that point.

2.4. Baseline and Alternative Scenarios

Three numerical dynamic models are solved to estimate the potential gains from optimal conjunctive management of groundwater and surface water from on-farm water storage systems.

[5]Personal correspondence with Mr. Evan Gregory, ejg113@msstate.edu, Extension Associate, Department of Agricultural Economics, Mississippi State University.

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Table 2. Model parameters for Sunflower county, MS

Component	Parameter	Value
Water demand	Elasticity (E)	−0.13
	Initial quantity (acre-ft)	271,809
	Initial pumping cost ($/af)	16.28
Aquifer	Surface elevation (*SL*)	118
	Initial water table elev. (h_0)	77.91
	Base elevation (h_b, FSL)	−18.49
	Net recharge (r, acre-ft)	231,802
	Acres × specific yield (A_S)	89,344
	Return flow portion (α)	0.10
Sunflower, MS	Cropland acreage (*AG*)	356,887
Crop mix	Irrigation requirement (C_R)	0.58
	Soybean share	76%
	Corn share	14%
	Rice share	7%
	Cotton share	3%
Irrigation	Irrigated acres (2019)	265,178
	Soybean requirement (af)	0.50
	Corn requirement (af)	0.50
	Rice requirement (af)	1.63
	Cotton requirement (af)	0.32
	Application efficiency (ε)	0.54
Pumping	Cost parameter (c_0)	5.912
	Well coefficient (Q_0)	10,116
	Cost ($ per acre-ft per ft of lift)	0.54
OFWS	Capital recovery ($/acre)	244
	Opportunity cost ($/acre)	109
	Apply (*EC*, $/acre-ft)	3.76
Discount	Rate (δ)	0.02
Rainfed	Average returns (ρ, $/acre)	12.06

The "Baseline" model is a myopic optimization without OFWS. In this first case, a single agent has the goal of maximizing profit each agricultural season unconcerned with implications related to aquifer status in the future. In contrast to equation (6) in the model presented in Section 2.1, this solution follows the following profit maximizing condition:

$$\beta_1 - \beta_2 w - C_g(h) = 0. \tag{16}$$

In this case, groundwater w is applied up to the point where its marginal benefit in terms of yield gains equals the marginal cost of extracting it.

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The "Myopic Optimization with OFWS" also maximizes profits each agricultural season but is allowed to build OFWS facilities at the costs stipulated in Table 2 and once land is placed into OFWS infrastructure, it cannot be reverted back to cropping. The two conditions to find the solution that link the two sources of water are

$$\beta_1 - \beta_2(w+s) - C_g(h) = 0, \text{and} \tag{17}$$

$$\beta_1 - \beta_2(w+s) - C_s(h) = \gamma \frac{3}{20} s. \tag{18}$$

The second condition indicates that the surface water is applied insofar the net benefit of applying water from the OFWS facility is sufficient to compensate for the capital and opportunity cost of the required infrastructure. Most articles on OFWS in this region are based on comparing outcomes based on these two conditions. Studies assessing application efficiency effects can be represented as shifts in the demand for irrigation water ($P\ (w+\ s)$) and those considering cost-sharing for OFWS structures can be represented as a change in parameters in the right-hand side of the second condition (18). Hence, our approach includes and extends the existing class of analysis of OFWS in the Delta area of Mississippi.

The "Horizon Optimization with OFWS" case maximizes the net present value (NPV) of the sum of the stream of profits from irrigation over a 200-year horizon. Because the pumping cost depends on aquifer levels over time, this solution accounts for the effect decisions made in a given season could have on future profits. This solution satisfies all the optimality conditions from equations (5) to (13). Some studies in the region include a time horizon (30 years or less) that is too short to capture the long-term implications of current irrigation and water infrastructure decisions.

In all cases, the solutions are limited by the land use constraint in the first component of equation (11). By comparing the three scenarios, we can identify the potential gains from optimal management and how closely producers can be expected to endogenously establish the required OFWS infrastructure in the county.

2.5. The Value of Conserved Groundwater

Kovacs et al. (2014) include a buffer value of groundwater estimate in their optimal management framework to account for the social value of retaining groundwater in the aquifer rather than applying it for irrigation. They assume the buffer value of groundwater is constant over time at an estimated \$5.19 per acre-foot of groundwater. Their formulation follows Tsur's (1990) single-period model of the stabilization value of groundwater applied for irrigation with stochastic surface water supplies. However, Tsur indicates that this formulation is not a "legitimate description of a dynamic situation if" abstractions exceed the rate of natural recharge and the aquifer serves the entire area that overlays it, in which case "dynamic modelling will need to be employed."

The MRVAA is depleting because abstractions exceed the rates of recharge and the entire area that overlays it uses its groundwater for irrigation. Furthermore, irrigated agriculture in Sunflower County, MS, employs groundwater almost exclusively. Consequently, an adequate estimate for the value of conserved groundwater may be obtained from the scarcity value resulting from the dynamic optimization problem. In this dynamic optimization framework, the costate variable ψ is interpreted as the monetized value an extra foot of saturated thickness adds to the NPV, which can be converted to a volumetric amount in acre-feet or capitalized as land value per acre.

2.6. Sensitivity Analysis

We run the three scenarios under alternative values for (1) the real discount rate at 3 and 5%; (2) higher rainfed returns (24.58 per acre); (3) no return flows to the aquifer from water applied

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Table 3. Summary results of three optimization scenarios

Scenario	Baseline	Myopic with OFWS	Planned Optimal OFWS
Net present value (million USD)	14,452	18,710	19,230
Gains from management (million USD)		4,258	4,778
Groundwater use (million AF)	59.7	58.9	54.6
Groundwater savings (AF)		811,662	5,053,660
Total irrigation (million AF)	59.7	74.3	73.7
Decline in saturated thickness (ft)	Up to 83	57	10
Initial costate value $\left(\$ \frac{\psi}{\text{acre}}\right)$			24

for irrigation; and (4) alternative rates of net natural recharge (0.5189 ± 0.04 ft. per year). The difference between the three scenarios under each alternative valuation is presented.

3. Results and Discussion

Table 3 summarizes the county-wide outcomes from each of the optimization scenarios. Over the extended planning horizon of 200 years, over $4.7 billion in gains from optimally managing the alluvial aquifer with the use of OFWS are possible county-wide. Compared to the myopic case with OFWS, the gains from optimally managing the intertemporal allocation of the groundwater stocks and OFWS infrastructure yields over $500 million gains in producer surplus.

Although periodic profit maximization with OFWS available captures a substantial portion of the potential farm profit gains from management, the results in terms of resource conservation are not as favorable. Of the more than 5 million AF of groundwater savings achievable under the optimal scenario, seasonal profit maximization with OFWS is capable of saving less than 1 million AF of groundwater relative to the baseline scenario.

Because OFWS captures pluvial and irrigation runoff, it is capable of sustaining larger areas and levels of irrigation than a slowly recharging aquifer. In terms of the total volume of water applied for irrigation, the optimal plan allows over 23% more irrigation water applied than the baseline. This is a remarkable volume given that it simultaneously allows over 5 million AF of groundwater saved over the planning horizon.

The bottomline in groundwater conservation is the expected decline in saturated thickness of the aquifer. The optimal extraction and OFWS infrastructure plan results in a decline of approximately 10 ft. in the saturated thickness at the end of the planning horizon. The baseline scenario indicates an alarming lowering of the water table of up to 83 ft. which translates to periodic groundwater exhaustion. With the expansion of OFWS under the seasonal profit maximization scenario, the saturated thickness is reduced by approximately 57 ft. At the initial period, the costate variable ψ indicates that agricultural land in Sunflower County, MS, is approximately $24 per acre more valuable if the aquifer is optimally managed with OFWS.

Figure 2 illustrates the drastically different depletion paths under the alternative scenarios. For the first few decades, the depletion paths under the baseline and the myopic optimization with OFWS are virtually identical but result in drastically different aquifer outcomes in the long term. This highlights a point made earlier about the shortcomings of using relatively short optimization horizons to evaluate effects of practices that have long-term implications. Furthermore, the time paths of the variables of interest are also relevant to the analysis of aquifer conservation practices and initiatives, which should not be limited exclusively to comparisons of resulting NPV comparisons of costs and benefits, particularly private costs and benefits. While the monetary benefits of OFWS are more heavily discounted in the future when they are more beneficial, the aquifer

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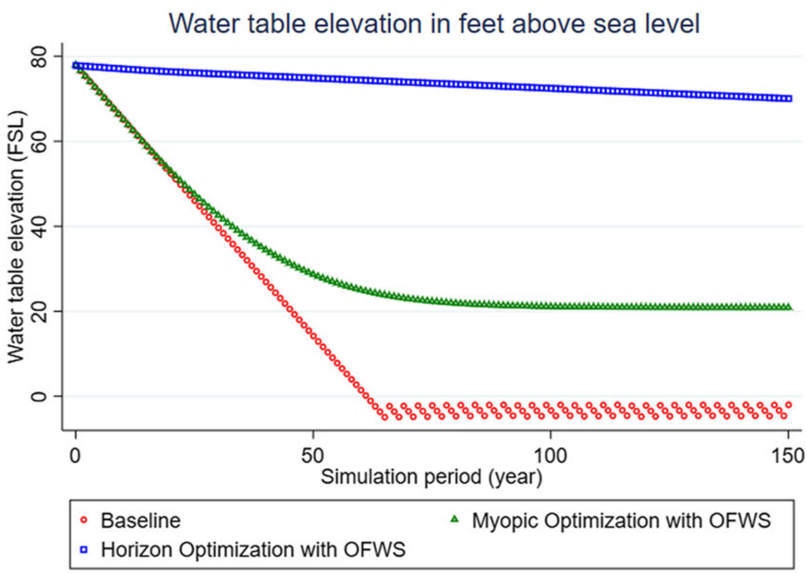

Figure 2. Comparison of aquifer decline paths under different scenarios for Sunflower County, MS.

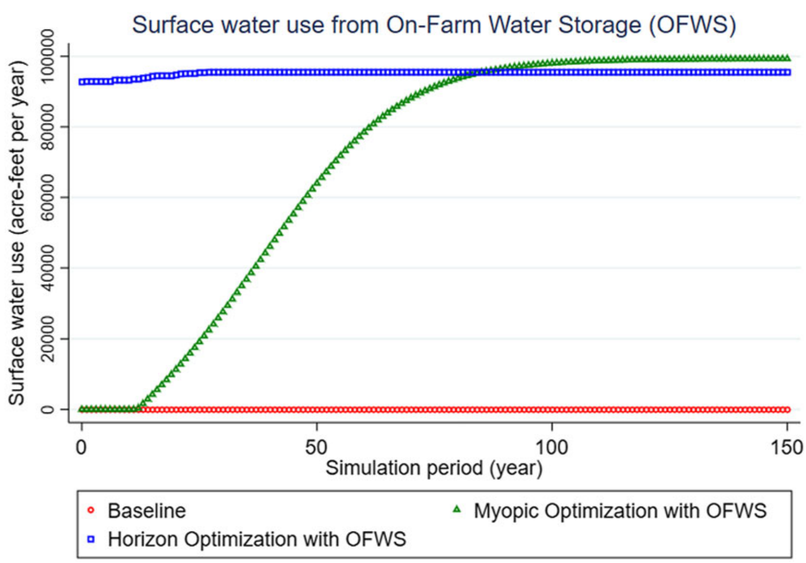

Figure 3. Comparison of surface water use paths under different scenarios for Sunflower County, MS.

outcomes suggest they are an attractive option for society—even if not so much to individual producers.

With respect to the establishment of OFWS infrastructure, Figure 3 illustrates the paths of surface water use from this source over time. Under the optimal plan, the infrastructure is rapidly developed while the myopic optimization with OFWS results in drastic underinvestment for several decades until the aquifer depletion and the increasing pumping costs drives rapid OFWS infrastructure development culminating in long-term over-investment.

The pattern of groundwater use shows the story of depletion (see Figure 4) where the aquifer is tapped as much as possible in the baseline until it reaches a level in which periodic drastic

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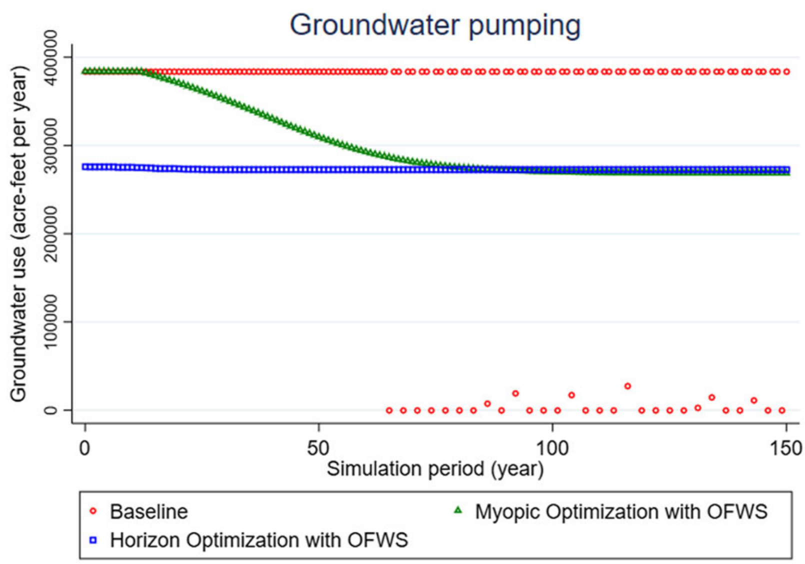

Figure 4. Comparison of groundwater use paths under different scenarios for Sunflower County, MS.

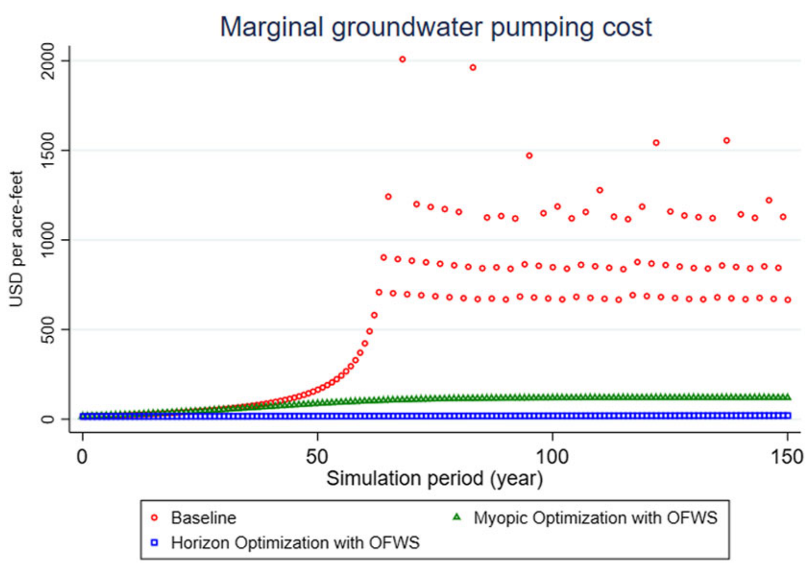

Figure 5. Comparison of marginal cost of pumping groundwater paths under different scenarios for Sunflower County, MS.

reductions in groundwater use are required due to exhaustion. The risk implications of the likelihood of encountering low aquifer levels and drought conditions would be an interesting line of research. With the eventual development of OFWS under myopic optimization, the complete depletion is avoided and subsequent reductions in abstractions are observed in which groundwater use is even lower than under the optimal management plan.

As pumping lift distances increase and groundwater yields decline, the marginal cost of pumping groundwater increases more than proportionally to depletion. This drives the expansion of OFWS in the myopic scenario as illustrated in Figure 5. In the long run, pumping cost is periodically prohibitive in the baseline scenario even if the aquifer is not completely depleted. Because

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Table 4. Summary of gains from management under alternative parameter values

	Management Gains with Respect to:			
	Baseline Scenario		Myopic with OFWS Scenario	
	Water Savings (in Million AF)	Producer Surplus (in Million USD)	Water Savings (in Million AF)	Producer Surplus (in Million USD)
Discount rate (3%)	2.7	2,104	2.3	1,193
Discount rate (5%)	2.2	734	1.8	601
High rainfed returns ($24.58 per acre)	3.2	4,683	2.7	2,042
Not return flows ($\alpha = 0$)	3.7	6,404	2.4	2,286
Return flow ($\alpha = 0.1835$)	4.2	6,501	2.3	2,727
Low aquifer recharge	4.3	5,671	4.2	2,189
High aquifer recharge	6.2	3,653	5.1	1,908
Demand elasticity ($E = -0.17$)	2.9	8,564	1.5	2,982

the plan that optimally manages the aquifer and OFWS allows for aquifer conservation, pumping costs are much lower in the long run which equates to higher future periodic farming profits.

3.1. Sensitivity Analysis Results

To assess how sensitive the main results are to critical assumptions and parameter values, we run the three scenarios under alternative values for (1) the real discount rate at 3 and 5%; (2) higher rainfed returns (24.58 per acre); (3) no return flows to the aquifer from water applied for irrigation; (4) higher return flows to the aquifer (83.5% higher than assumed); (5) alternative rates of net natural recharge (0.5189 ± 0.04 ft. per year); and (6) a higher groundwater pumping cost elasticity in the initial period ($E = -0.17$). Table 4 details the gains from optimal management under the different scenarios.

The gains from management are obtained by comparing the outcomes from the optimal management solution to that of the baseline and the myopic with OFWS scenarios. Comparing across scenarios provides a sense of the gains obtained from the use of OFWS and the gains from optimal temporal allocation of the groundwater resource.

Higher discount rate, in terms of the dynamic program, indicates the degree to which current benefits are preferred over benefits for future generations. Consequently, it is expected that higher discount rates would result in less conserved water and smaller producer surplus gains relative to myopic outcomes. This is confirmed by observing lower levels of groundwater use reductions with 2.7 million acre-feet of groundwater saved when using a 3% discount rate and 2.2 million acre-feet saved when compared with the baseline scenario. Similarly, comparing the optimal management outcomes to the myopic with OFWS scenarios, groundwater savings of 2.3 and 1.8 million acre-feet, respectively, for the 3 and 5% discount rates. In terms of the producer surplus gains, the sensitivity analysis shows lower levels under the higher discount rates, as expected.

When there is no return flows ($\alpha = 0$), the amount of irrigation water applied leaves the basin entirely via crop evapotranspiration or runoff. Consequently, when irrigation water from OFWS is used for irrigation the only benefit comes from substituting otherwise pumped groundwater, but loses its ability to assist in recharging the aquifer. Nonetheless, the water savings are significant against the suboptimal scenarios with 3.7 and 2.4 million acre-feet of groundwater saved when compared to the baseline and myopic with OFWS cases. In terms of producer surplus, the myopic with OFWS scenario is capable of capturing substantial gains from the baseline case, but it is still noticeably suboptimal in terms of overall groundwater use.

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When return flows are higher ($\alpha = 0.1835$), a larger portion of the total irrigation water applied returns to the aquifer which reduces the negative impact of over-pumping from period to period. In terms of total groundwater use, the implication is that higher return flows allow for higher groundwater use, which is reflected in the 4.2 million acre-feet difference in total pumping in baseline with respect to the optimal plan. Because the myopic with OFWS scenario allows for both substitution of groundwater and a portion of the applied surface water to recharge the aquifer, the difference in groundwater use is smaller at 2.3 million acre-feet.

The effect of the net rate of natural recharge of the aquifer can also be appreciated from these results. A reduction in the rate of recharge has two effects, it reduces the total magnitude of the resource to be managed and increases the importance of optimally allocating the resource over time. These effects can be observed when comparing the low and high aquifer recharge outcomes. Because the high recharge rates equates to a larger stock to manage over time, the optimal plan results in larger amounts of the resource conserved. In contrast, because more of the groundwater extracted is replenished with higher aquifer recharge, the penalty for over-extracting earlier is lower when the annual aquifer recharge is higher. Consequently, the optimal plan returns larger gains when the penalty for over-extraction are larger (i.e., with lower recharge).

We also run the three scenarios under alternative groundwater pumping elasticity scenario ($\mathrm{E} = -0.17$) at the observed groundwater level use and pumping cost at the initial period. The difference in groundwater use if 2.9 and 1.5 million acre-feet with respect to the baseline and myopic with OFWS scenarios, respectively. This higher sensitivity to the cost of groundwater pumping also result in larger gains from optimally managing the aquifer over the life of the resource.

4. Conclusion

Aquifer depletion is a problem that concerns private producers and public agencies. Groundwater pumping from an individual grower has little influence on aquifer-wide outcomes causing individual changes in pumping behavior to have negligible effects on aquifer depletion slowdown. Consequently, public agencies or grower collectives must be engaged to induce beneficial practices on a broader scale that could have significant effects on aquifer depletion. Research into the optimal groundwater pumping and storage policy is helpful to inform these public agencies or grower collectives on the optimal allocation of funds directed towards incentives to adopt practices and investments in developing water resources.

Because the greatest benefits of some conservation practices, such as OFWS, occur over long time horizons while their costs are faced upfront, the compound discounting of benefits in relatively short planning horizons masks the economic and conservation merits of such practices. Conservation practices need to be evaluated based not only on NPV bottomline but also based on the time paths taken by the variables of interest. Consequently, dynamic modeling is required to adequately analyze the economics of a depleting aquifer.

The benefits of optimal management are greater when the greatest amount of the resource and the longest planning horizons are available. This means that time is of the essence for a depleting aquifer. A clear insight is that the more depleted the aquifer or the later an optimal management program starts, the lower the potential gains from managing it are.

This paper examines the merits to develop on-farm water storage with tailwater recovery infrastructure in an area with acute alluvial aquifer depression. The results indicate that these structures are worth developing on a broader scale. Existing literature assessing field-level or relatively short time horizons (in the Delta of Mississippi) have found that OFWS is too costly relative to the private benefits for which those studies account (Falconer, Lewis, and Krutz, 2015; Falconer, Tewari, and Krutz, 2017; Omer et al., 2019).

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The current conditions of the alluvial aquifer in Arkansas and the trajectory it took over time are a sign of warning for Mississippi. Alluvial aquifer depletion has been more acute there than in Mississippi, which marks an opportunity for the Delta in Mississippi to "get ahead" of that curve in terms of deploying groundwater-conserving practices such as OFWS. Several studies find that OFWS is a profitable option in Arkansas when there is limited water availability (Kovacs and Mancini, 2017; Popp et al., 2003; Wailes et al., 2003), adequate cost-sharing incentives are available (Kovacs et al., 2014; Popp et al., 2003), groundwater use is taxed (Kovacs et al., 2014), or a portion of the stock of water in the OFWS recharges the aquifer (Kovacs et al., 2015). The findings in this paper suggest an active role for public agencies and producer collectives to overcome the individual grower investment hurdles and "get ahead of the curve" with regards to groundwater conservation.

The main caveat in the model is that it underestimates OFWS benefits such as nutrient capture and its benefits in alleviating the hypoxic zone in the Gulf. For example, Popp et al. (2003) estimate the amount of annual per acre movement of pesticides and nutrients from rice fields in Arkansas; Kovacs et al. (2014) estimates the value of phosphorous and sediment conservation associated with OFWS in Arkansas; and Pérez-Gutiérrez, Paz, and Tagert (2017) investigates the ability of OFWS to mitigate off-site nutrient movement in Sunflower County, MS. Although dynamic, the formulation is deterministic and further extensions incorporating stochastic dynamic programing would be useful. Presumably, there would be additional risk-management benefits to having multiple sources of irrigation water in anticipation of the effects of climate change.

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