GROUNDWATER EXTERNALITIES WITH ENDOGENOUS WELL DEEPENING

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ABSTRACT. We develop a dynamic groundwater model that incorporates both groundwater pumping and investment in deeper wells and apply the model to the arid, alluvial aquifer region of Northern India that is experiencing rapid depletion. We compute the potential benefits of regulating groundwater use by comparing the net benefits of groundwater under optimal management to the net benefits under a common pool regime with two different cost structures: one with flat electricity tariffs, which are widespread in India, and a second with full marginal cost electricity pricing. Using numerical simulation, we find that the opportunity to invest in deeper wells significantly exacerbates the common pool problem and suggests the potential for large benefits (66% of common pool benefits) from optimally managing groundwater use or new drilling. Flat tariffs exacerbate the problem, but large gains (almost 23%) remain even if farms are charged the full marginal cost of electricity.

Keywords: groundwater; India; irrigation; common property resource; numerical simulation; dynamic optimization; well capacity

1. INTRODUCTION

Over the past fifty years, the use of groundwater for irrigation has dramatically increased in developing countries like India and China (Siebert *et al.*, 2010). Increased groundwater irrigation has enabled higher and more consistent crop yields, which in turn has improved food security and reduced poverty (Rosegrant & Cline, 2003). However, this increase in groundwater use has led to falling water levels in many places, leading to widespread concern about the long-term sustainability of irrigated agriculture (Hanjra & Qureshi, 2010).

These concerns have been especially dire in India, where groundwater use has increased by 500% over the past fifty years (Garduño & Foster, 2010). The Central Groundwater Board of

Date: 01/22/18.
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India estimates that fifteen percent of the administrative blocks in India extract more water than is replenished (Central Ground Water Board, 2014) and there is widespread concern about rapid depletion (Lall *et al.*, 2011; Shah, 2012; Mukherji *et al.*, 2013; Fishman *et al.*, 2015b). Evidence suggests these dropping groundwater levels have increased poverty and conflict and decreased agricultural profits (Sekhri, 2013, 2014).

On one level, this pattern of falling groundwater levels is not surprising economically, since groundwater is a common pool resource and is likely to be overused in the absence of mechanisms to restrict usage. On the other hand, these concerns about overuse are in direct contrast with much of the groundwater economics literature, which finds that the size of the common pool externality is relatively small in real world scenarios. This result, first identified by Gisser & Sanchez (1980), suggests that while groundwater levels may be falling faster than optimal, the resulting welfare losses are negligible. This result has been termed the Gisser-Sanchez effect and has been found empirically to hold in a diverse array of contexts (Koundouri, 2004; Pfeiffer & Lin, 2012; Lin Lawell, 2016; Sears & Lin Lawell, forthcoming).

In this paper, we explore this apparent contradiction between the economic theory and the reality on the ground in India. We construct a Gisser-Sanchez style model that includes three critical features of the groundwater situation in India: first, that changes in well capacity, rather than the cost of extraction, are the primary impact of reduced water levels on farmers; second, that well capacity can be increased through endogenous investment in well deepening and stronger pumps; and third, that subsidized flat electricity tariffs exacerbate the common pool externality. We then parameterize our model using numbers that fit the arid alluvial aquifer region of Northwest India and estimate the size of the externality losses.

Our model differs from the typical groundwater model in that farmers who behave "myopically" with respect to the impact of their pumping on future groundwater levels still face a dynamic investment problem regarding their decisions about well investment. We thus compare an optimal management regime in which both groundwater pumping and well investment decisions are made optimally, to an unregulated common pool regime in which individual farmers ignore the impact of their pumping on future water levels, but make decisions about well investment based on rational expectations about future groundwater levels.

We find that instituting optimal management increases the present value of the social net benefit of irrigation by 66%, relative to the common pool situation with flat electricity tariffs. Approximately half this gain could be realized by replacing the flat tariffs with marginal cost pricing of electricity, but we estimate that optimal management will increase the benefits relative to a common pool regime with real electricity costs by almost 23%, still a sizable gain. We further assess the impact of several specific parameters on our results and find that differences in the estimated gains remain non-negligible across a wide variety of parameter values.

Our paper contributes to the literature that investigates the robustness of the Gisser-Sanchez effect to changes in the model. While much of the work has confirmed the Gisser-Sanchez result, several notable exceptions identify larger gains to management. These include Brill & Burness (1994) who incorporate increasing demand, declining well yields, and low social discount rates, Koundouri & Christou (2006) who consider an aquifer close to depletion without a viable backstop, Tsur and Zemel (1995; 2004) who consider the buffer value of groundwater in the presence of uncertainty and the possibility of irreversible damage, and Guilfoos *et al.* (2013) who simulate a spatially explicit aquifer and find relatively large (27%) gains from management if farmers behave myopically. Other authors have focused on investments or adaptations farmers may make to reduce groundwater use. Burness & Brill (2001) consider investment in efficient irrigation technology and Kim *et al.* (1989) look at changes in the mix of crops grown over time. Both studies confirm the Gisser-Sanchez result, finding small inefficiencies under the common pool regime. Instead of analyzing investments or adaptations that reduce the demand for water, we focus on a lumpy investment decision that mitigates the impact of falling water levels on farmers.

We also contribute to a growing literature on the importance of well capacity for understanding the implications of groundwater depletion. Brill & Burness (1994) provide early evidence that declines in well yield as water levels fall can lead to large gains from management. More recently, Foster et. al (2014; 2015a; 2015b) emphasize the importance of well capacity for intra-annual decisions about crop choices. Manning & Suter (2016) include the effect of neighbors on well capacity in a spatially explicit three cell aquifer for a basin in Colorado and find small gains from management (2%) when farmers behave optimally.[1] We extend this work by applying the ideas in a developing country context and incorporating the option to overcome reductions in well capacity through investment in deeper wells and stronger pumps.

Our paper also contributes to the literature on the groundwater situation in India. Previous work has analyzed how subsidized, flat electricity tariffs are a market failure that increases groundwater extraction beyond the socially optimal level (Badiani *et al.*, 2012; Fishman *et al.*, 2016; Badiani & Jessoe, 2017).[2] Separate work has analyzed the external social costs of repeated well deepening by farmers in response to falling groundwater levels (Shah, 2012; Fishman *et al.*, 2015b). We add to this literature by analyzing these two features simultaneously in a dynamic framework. Critically, we find that these market failures compound each other: electricity subsidies substantially exacerbate the common pool externality by increasing (socially wasteful) investment in deeper wells and stronger pumps. This result is in contrast to earlier work that has found relatively small deadweight losses from the electricity subsidies in a static framework (Badiani & Jessoe, 2017).

The rest of the paper is organized as follows. In Section 2, we provide additional background on the groundwater situation in India. In Section 3, we construct a stylized model of groundwater use and investment. In Section 4, we describe the specific functional forms and parameters used in numerical simulations. In Section 5, we present the results of our numerical simulations for our baseline simulation results and several sets of comparative statics. We also discuss the robustness of our results to certain changes in the structure of our model. In Section 6, we discuss the implications of our results as they relate to groundwater policies. In Section 7, we discuss next steps and the broader applicability of our simulation results.

2. Background

The over-exploitation of groundwater in India has been especially problematic in the arid alluvial aquifer regions of Northern India, which comprise the states of Punjab, Haryana, parts of

[1] Recent work by Merrill & Guilfoos (2018) also addresses this question.

[2] These papers that analyze the impact of flat electricity tariffs on groundwater are part of a larger literature that explores the impact of energy prices on water usage and groundwater extraction (Zhu *et al.*, 2007; Zilberman *et al.*, 2008; Pfeiffer & Lin, 2014b).

Rajasthan and northern Gujarat (Shah, 2012). While the existing groundwater literature captures many important features of the groundwater problem, it does not adequately describe the situation in this region. In Gisser and Sanchez's work, the groundwater externality exists because pumping by individual farmers lowers the water levels and thus increases the extraction costs for their neighbors. At the same time, these falling water levels provide feedback that limits the size of the externality: as costs increase, farmers reduce their pumping, slowing the decline. This continues until consumptive water extractions reach the natural inflow rate and the aquifer reaches a steady-state. In the optimal management regime, steady-state extraction is the same (the natural inflow rate), but pumping will slow faster so that the steady-state water level is higher and extraction costs are reduced. The size of the common pool externality is thus largely a function of how different the steady-state extraction costs are. Notably, since access to groundwater is limited to farmers with land overlying the aquifer, a degree of exclusivity exists. Instead of an open-access resource, for which we would expect all benefits to be competed away, groundwater resembles a common pool resource that will be overused, but will still yield positive net benefits in the steady-state.

In our study region, the relationship between water levels and farm profits is different. In this region, as in much of India, the government provides generous electricity subsidies, amounting to roughly 85% of the actual cost of electricity. Furthermore, farmers are charged a flat monthly tariff for electricity rather than a per unit charge (Badiani *et al.*, 2012; Badiani & Jessoe, 2017).[3] As water levels fall, farmers face no change in the direct cost of extracting water, due to the flat electricity tariffs. Instead, the drop affects farmers by reducing the volume of water they can pump from their well in a given amount of time. Recent work has emphasized the importance of this well capacity effect in other regions (Foster *et al.*, 2014, 2015a,b; Manning & Suter, 2016; Hrozencik *et al.*, 2016; Merrill & Guilfoos, 2018).

In response to this declining yield, farmers can reduce the acreage they irrigate or deepen their well and purchase a more powerful pump. As they deepen wells, farmers incur a large capital cost. This occurs both due to the deepening of the well and due to the purchase of a new, more powerful pump that can pump to the greater depth. Moreover, the deeper wells and larger pumps

[3]This monthly tariff is based on the capacity of the pump.

require more maintenance costs and increase the flat electricity tariff farms face. The annualized costs of this repeated investment in deepening wells have been estimated to be as high as 25% of the average annual net income from crops (Lall *et al.*, 2011). These investments allow the farmers to maintain their previous extraction levels and thus circumvent the self-limiting feedback effect that lowers extraction in response to falling water levels, at least as long as the well deepening investments remain profitable. At some point, farmers may have to migrate or exit agriculture, which is problematic from an equity point of view because poorer farmers have worse outside options (Kishore, 2014; Fishman *et al.*, 2015b).

Although the importance of well capacity is receiving increased attention in the groundwater economics literature, the linkage between depths and investment has not been explored in detail. These repeated investments function like a form of entry. As water levels fall, farmers must continually "re-enter" the irrigation industry by upgrading their technology in the form of deeper wells with stronger pumps. We should expect this entry to continue as long as the net benefit of entry is positive. But each decision to "re-enter" lowers the profits of all neighbors because it reduces the length of time before another round of investment will be required.[4] The net benefit of irrigation to individual farms, inclusive of the investment costs, will eventually be driven close to zero. Moreover, these investments serve only to maintain a prior status quo and can only temporarily address the fundamental challenge in the region: that the available water is not sufficient to irrigate all the land farmers wish to cultivate.

Based on these observations, we develop a model that captures the relationship between three essential features of the groundwater use situation in Northern India. First, farmers in the region tend to irrigate as much land as they can given their land holdings and well capacity. Second, farmers face a sequential investment decision as they decide when and if to incur investments in deeper wells. These investments are described as "chasing the water levels," and observers note that they do not allow farmers to expand their irrigated area, only to maintain their prior pumping in the face of reduced capacity in their existing well. Profit margins are thus continually falling as investments accumulate. Third, because groundwater is a common pool resource, farmers have

[4] Liu *et al.* (2014) incorporate an entry decision into a spatially explicit laboratory experiment groundwater exploitation game and observe inefficiently high entry levels.

no incentive to limit their use today to keep future water levels high; they anticipate that their own pumping will have minimal impact on future water levels.

3. Model

Following the approach of the Gisser and Sanchez literature, our analysis compares the net benefits of two alternate regimes. We simulate the path of groundwater levels, extractions, and investment over time in a common pool regime. We then compare those levels, and the resulting net benefit from the aquifer, to those obtained if a benevolent dictator selected extraction and investment levels for each farmer in every period. This gives an upper bound on the gains that could result from implementing regulations. In this section, we present an analytical model describing extractions and investments under the two regimes. In Section 4, we specify functional forms for all our relationships and parameterize the model.

3.1. **Farmers, investment, and groundwater.** We consider a groundwater aquifer with $n = 1,...,N$ individual farmers. We simplify the investment decision by granting farmers access to a series $i = 1,...,I$ of technologies for extracting water. The technologies consist of the combination of a well of a particular depth and a pump of a particular horsepower. They are ordered in terms of increasing maximum depth and therefore also in terms of increasing cost. We model well deepening as a choice between discrete technologies to emphasize the role of the substantial fixed investment costs associated with any deepening. We abstract away from the decision of how deep to drill at a given point in time by considering a series of fixed feasible depths.[5] At time t, the current technology state on farm n is s_{nt}. The current pumping depth in the aquifer is given by d_t. The maximum amount of water that a farm can extract each year depends on both the current pumping lift and the current technology state and is given by $W(d_t, s_{nt})$, where $s_{nt} > \widetilde{s}_{nt}$ implies that $W(d_t, s_{nt}) \geq W(d, \widetilde{s}_{nt})$.

We abstract away from many details of the annual decisions made by farmers and define the instantaneous net benefit of water use as $B(w_{nt}, d_t, s_{nt})$, where w_{nt} is the the amount of groundwater used. We assume that the gross benefits of water use are constant across technologies and depths

[5]See Section 5.3.1 for a discussion of how changes in the fixed depths considered influence our results.

but that d_t and s_{nt} affect the annual net benefit by altering the energy needs and electricity charge farms face.[6] This function reflects the highest instantaneous net benefit a farmer can achieve from using w_{nt} in a given period and subsumes choices about how much to irrigate and what crop to plant. Moreover, we abstract away from farm level variation in the benefits and costs of water use and assume that all farms with same technology have the benefit function.

In each period, farmers choose their next-period technology, a_{nt}. Each farmer has an investment cost parameter ω_n that reflects farmer heterogeneity in the cost of switching technologies due to variation in characteristics like wealth, information, credit, and land characteristics. The cost for farmer n of choice a_{nt} given current technology s_{nt} is $C(a_{nt}, s_{nt}, \omega_n)$, with $C(\cdot)$ non-decreasing in ω for all a and s. If a farmer elects to not change technology, then $a_{nt} = s_{nt}$ and the cost represents the annual maintenance cost. If a farmer chooses to change technologies, then $a_{nt} \neq s_{nt}$ and the cost is the switching cost. The technologies are ordered in terms of both increasing limits and increasing investment cost and this ordering is constant for all farms. Thus $i > j$ implies that $C(i,k,\omega_n) \geq C(j,k,\omega_n)$ for all $k \neq i, j$ and all ω_n and $W(d,i) > W(d,j)$ for all d. Finally, maintenance costs are similarly ordered so that $i > j$ implies that $C(i,i,\omega_n) \geq C(j,j,\omega_n)$ for all ω_n. Under this setting, the farmers with lower values of ω will be more likely to invest in the better technologies.

We track N individual state variables (current well technology on each farm) and one aggregate state variable (pumping lift in the aquifer). The state equation for well technologies is straightforward; next period's technology on farm n is determined by this period's choice, e.g. $s_{nt+1} = a_{nt}$. Since our focus is on the broad relationships between the pumping cost externality, well capacity and investment, we follow much of the Gisser-Sanchez literature and use a simplified hydrological model. Specifically, we assume that pumping depths instantly equate throughout the aquifer according to the equation

$$d_{t+1} = d_t + \frac{(1-\alpha)\left(\sum_{n=1}^{N} w_{nt}\right) - \rho}{\phi} \tag{1}$$

[6] In some of our simulations, we also allow farmers to consider a different net benefit function than the social planner to capture the real world existence of flat, subsidized electricity tariffs.

where ρ is the natural rate of inflow into the aquifer (assumed constant over time), α gives the percentage of water applied to crops that percolates back to the aquifer, and ϕ describes the volume of net water extraction that results in a one meter increase in pumping depths.[7]

3.2. **Common pool groundwater use.** In a common pool regime, individual users are small relative to the aquifer and ignore their own impact on the future level of the aquifer. Unlike the typical groundwater problem with a bathtub aquifer, the individual farmer's problem is dynamic because the farmer must decide when to switch technologies. In each period, individual farmers take the path of the future pumping depths ($\mathbf{d}$) as given and choose how much to pump this period (w_{nt}) and what technology to use next period (a_{nt}).

3.2.1. *Annual water use.* Since farmers take the path of depths as given, water use decisions are made on a year by year basis and depend only on the farm's current technology and the current pumping depth. The Lagrangian for farmer n's common pool water use problem is

$$\mathscr{L}\left(w_{nt}, \lambda_{nt}^{CP}; d_t, s_{nt}\right) = B\left(w_{nt}, d_t, s_{nt}\right) + \lambda_{nt}^{CP}\left(W\left(d_t, s_{nt}\right) - w_{nt}\right) \tag{2}$$

where λ_{nt}^{CP} is the Lagrange multiplier for the limit on water use on farm n at time t. The first-order conditions are

$$\frac{\partial B}{\partial w_{nt}}\left(w_{nt}, d_t, s_{nt}\right) - \lambda_{nt}^{CP} = 0 \tag{3}$$

$$\lambda_{nt}^{CP}\left(W\left(d_t, s_{nt}\right) - w_{nt}\right) = 0 \tag{4}$$

with $\lambda_{nt}^{CP} \geq 0$ for all n and t. Let $w^{*CP}\left(d_t, s_{nt}\right)$ be the solution to this system of equations and let

$$B_{nt}^{*CP}\left(d_t, s_{nt}\right) = B\left(w_{nt}^{*CP}\left(d_t, s_{nt}\right), d_t, s_{nt}\right) \tag{5}$$

be the optimized value.

[7] Like much of the groundwater literature, this model simplifies the true hydrology. Papers exploring the importance of spatially explicit models include Saak & Peterson (2007); Brozović *et al.* (2010); Guilfoos *et al.* (2013); Hrozencik *et al.* (2016); Liu *et al.* (2014); Manning & Suter (2016); Merrill & Guilfoos (2018). Spatially explicit models are difficult to solve even when considering only groundwater depth and usage due to the large increase in the number of required state variables. A spatially explicit model incorporating investment would require twice as many state variables as one incorporating only groundwater depth and usage and would be numerically infeasible.

Farmer n's investment problem is to solve

$$\max_{a_{n1},\cdots,a_{n\infty}} \sum_{t=0}^{\infty} \delta^t \left(B_{nt}^{*CP}(d_t, s_{nt}) - C(a_{nt}, s_{nt}, \omega_n) \right) \text{ subject to } s_{nt+1} = a_{nt} \tag{6}$$

taking $\mathbf{d}$ as given. We reformulate this problem as a discrete time, discrete choice decision problem using dynamic programming. This yields the dynamic programming equation

$$V^{CP}(s_n, n, t; \mathbf{d}) = B_{nt}^{*CP}(d_t, s_{nt}) + \max_{a_n \in \{1,..,I\}} \left\{ \delta V^{CP}(a_{nt}, n, t+1; \mathbf{d}) - C(a_{nt}, s_{nt}, \omega_n) \right\} \tag{7}$$

where $V^{CP}(s, n, t; \mathbf{d})$ is the (unknown) continuation value in the common pool regime to farmer n of technology state s at time t, given that pumping depths are expected to follow the path $\mathbf{d}$. Since this is a discrete choice, we cannot characterize the solution using calculus. Farmer n currently using technology i will maintain that technology as long as the investment cost is greater than or equal to the discounted difference in continuation value, or as long as

$$C(j, i, \omega_n) - C(i, i, \omega_n) \geq \delta \left(V^{CP}(j, n, t+1; \mathbf{d}) - V^{CP}(i, n, t+1; \mathbf{d}) \right) \tag{8}$$

for all $j \neq i$. As this inequality indicates, farmers consider the effect of their investment choices on their ability to extract water in the future and the impact that will have on their future profits. However, since they take the depth trajectory as given, they do not consider the impact their increased pumping will have on future water levels. Yet over time, the combined impact of water use and technology choice collectively determine the path of pumping depths. We assume that farmers rationally predict the impact of all farmers' decisions on future depths and thus require that

$$d_{t+1} = d_t + \frac{(1-\alpha)\left[\sum_{n=1}^{N} w_{nt}^{*CP}\left(d_t, s_{nt}^{*CP}(\mathbf{d})\right)\right] - \rho}{\phi} \tag{9}$$

where $s_{nt}^{*CP}(\mathbf{d})$ is the optimized technology choice for farm n at time t for the problem described in Eq. (7). The full solution to the common pool problem is thus the joint solution to the system defined by Eqs. (3), (4), (7), and (9).[8]

[8] See Section 5.3.2 for a discussion of the common pool outcome when farmers naively expect water levels to remain constant at their currently level and update their expectations annually.

3.3. **Dynamic optimal management.** Under optimal management, decisions about both pumping and investment take into account the impact these decisions have on future groundwater levels and investment on other farms. The social planner selects trajectories of investment choices $\{\mathbf{a}_1,\mathbf{a}_2,\ldots\}$ and water use vectors $\{\mathbf{w}_1,\mathbf{w}_2,\ldots\}$ where $\mathbf{a}_t$ is an $N\times 1$ vector of technology choices with $a_{nt}\in\{1,\ldots,I\}$ and $\mathbf{w}_t$ is an $N\times 1$ vector of water use amounts. Let $g(\mathbf{w},d)=d+\frac{(1-\alpha)\sum_{n=1}^{N}w_n-\rho}{\phi}$ be the next period depth as a function of current period water use. The social planner has a mixed discrete/continuous optimization problem, which yields the nested optimization problem:

$$V(d,\mathbf{s})=\max_{\mathbf{a}}\left\{-\sum_{n=1}^{N}C(a_n,s_n,\omega_n)+\max_{\mathbf{w}}\left[\sum_{n=1}^{N}\left(B(w_n,d,s_n)\right)+\delta V\left(g(\mathbf{w},d),\mathbf{a}\right)\right]\right\} \tag{10}$$

subject to

$$0\leq w_n\leq W(d,s_n) \tag{11}$$

for all n.

Contingent on a vector of technology choices, the social planner will set water use on individual farms to solve the inner maximization problem, whose first-order conditions are

$$w_n\left[\frac{\partial B}{\partial w}(w_n,d,s_n)+\delta\frac{\partial V}{\partial d}\left(g(\mathbf{w},d),\mathbf{a}\right)\left(\frac{1-\alpha}{\phi}\right)-\lambda_n^{OPT}\right] = 0 \tag{12}$$

$$\lambda_n^{OPT}\left(W(d,s_n)-w_n\right) = 0 \tag{13}$$

$$\frac{\partial B}{\partial w}(w_n,d,s_n)+\delta\frac{\partial V}{\partial d}\left(g(\mathbf{w},d),\mathbf{a}\right)\left(\frac{1-\alpha}{\phi}\right)-\lambda_n^{OPT} \leq 0 \tag{14}$$

$$W(d,s_n)-w_n \geq 0 \tag{15}$$

As in most groundwater models, the condition for determining water use w_n under optimal management given in Eq. (12) differs from the common pool condition given in Eq. (3) through the inclusion of the $\frac{\partial V}{\partial d}(\cdot)$ term that captures the negative effect of today's pumping on water water levels. Thus, a farm with a given technology at a given depth will use more water in a common pool scenario than under optimal management. In much of the groundwater literature, the impact of this overpumping is small. In our setting, the impact is larger because overpumping is exacerbated in two distinct ways. First, in our simulations that reflect the on the ground reality in India, the cost of pumping that farmers consider in decision making is not the full social cost of pumping due to subsidized flat electricity tariffs. In this case, $\frac{\partial B}{\partial w}(w_n, d, s_n)$, which represents the instantaneous marginal net benefit of a given amount of water pumped from a given depth, is higher for the farmer than the manager, exacerbating the farmer's tendency to overpump. Second, as we demonstrate below, farmers are more likely to invest in deeper wells under the common pool scenario. A farmer with a deeper well is less likely to face a binding water constraint and thus likely to pump more water.

As in the common pool scenario, we can characterize investment through an inequality. Let $\tilde{\mathbf{a}}_t$ and $\hat{\mathbf{a}}_t$ be two investment vectors that differ only in investment on farm n and are optimized for all other farms and let $\tilde{\mathbf{w}}_t$ and $\hat{\mathbf{w}}_t$ be the associated vectors of optimal water use. Formally, let $\tilde{a}_{nt} = i$, $\hat{a}_{nt} = j$, and $\tilde{a}_{mt} = \hat{a}_{mt}$ for all $m \neq n$. The social planner will view $\tilde{\mathbf{a}}_t$ as optimal and maintain technology i on farm n if

$$\begin{aligned} C(j,i,\omega_n) - C(i,i,\omega_n) \geq & \sum_{n=1}^{N} B(\hat{w}_{nt}, d_t, s_{nt}) - \sum_{n=1}^{N} B(\tilde{w}_{nt}, d_t, s_{nt}) \\ & + \delta \left[V\left(g(\hat{\mathbf{w}}_t, d_t), \hat{\mathbf{a}}_t\right) - V\left(g(\tilde{\mathbf{w}}_t, d_t), \hat{\mathbf{a}}_t\right) \right] \\ & + \delta \left[V\left(g(\tilde{\mathbf{w}}_t, d_t), \hat{\mathbf{a}}_t\right) - V\left(g(\tilde{\mathbf{w}}_t, d_t), \tilde{\mathbf{a}}_t\right) \right] \end{aligned} \tag{16}$$

for all $j \neq i$. The lowest investment cost parameter for which this is true is the one for which this equation is satisfied with equality. The left hand side of this equation is the same as the left-hand side of the common property condition (Eq. (8)) and represents the investment cost associated with adopting technology j on farm n. The right-hand side of Eq. (16) captures the impact of three differences between the two investment regimes. The first two are unique to the optimal management problem, while the last has a natural analogue in the common property condition.

- **Changes in current period pumping** Note that current period technology choice $\mathbf{a}$ enters the solution to the optimal water use in Eq. (12) through its effect on $\frac{\partial V}{\partial d}(\cdot)$. Better technology lowers the negative effect of water level declines because water extraction limits will not fall as quickly. In other words, the user cost of water will fall as next period technology improves, leading to increased pumping today so $\tilde{\mathbf{w}}_t < \hat{\mathbf{w}}_t$. The first two terms on the right-hand side of Eq. (16) represent the benefit of this increased pumping at time t. Since farmers take the trajectory of water levels as given, no similar term appears in Eq. (8). By itself, this effect would tend to increase investment under optimal management.

- **Changes in future depth** Because investment will tend to increase pumping today, it will lower water levels in the next period, which lowers the continuation value. This effect is captured in the third term on the right-hand side of Eq. (16). Again, no similar term appears in Eq. (8). By itself, the effect would tend to reduce investment under optimal management.
- **Changes in future technology** The primary reason to invest in better technology is, of course, to gain access to the increased continuation value, which is represented by the final term of Eq. (16). A similar term appears on the right-hand side of Eq. (8). Note, however, that other changes in the problem indicate that this term will be higher under common property than under optimal management. Because pumping is higher in the common pool scenario, the rationally expected depth trajectory will include lower depths. This increases the value of the better technology and makes farmers more likely to invest in the common pool regime than under optimal management.

3.4. **A simplified optimal management problem.** The optimal management problem described above has $N+1$ state variables (the technology on each farm and the pumping depth) and $2N$ control variables (next period technology choice and water use on each farm). Numerical solution of the problem in this format is not feasible, so we conduct our numerical simulations using a simplified optimal management problem. First, since all farms with the same technology have the same instantaneous benefit of water use and the same impact on future water depth, we can consider only I water use variables, given by the vector $\mathbf{w} = (w_1, ..., w_I)$. For notational compactness, we also define a vector version of the instantaneous net benefit function $\mathbf{B}(\mathbf{w}, d) = (B(w_1, d, 1), ..., B(w_I, d, I))$ giving the instantaneous net benefit of water use on farms using each of the technologies as a function of the technology specific water use vector.

To further reduce the dimensionality of the problem, we move from considering technology on each individual farms to considering shares of farms using each technology. We define a vector

$\mathbf{z} = (z_1, ..., z_I)$ that gives the share of farms currently using each technology. Since the shares must sum to 1, this leaves us with I state variables: the pumping depth d and the $I-1$ shares that uniquely determine the full share vector $\mathbf{z}$. We can similarly reduce the number of control variables by considering the share of farms planning to use different technologies for the next period.The matrix of choice shares for the next period's technology is $\mathbf{X}$; its typical element x_{ij} is the share of farms currently using technology j that will use technology i next period.[9] The total cost of next period's technology choices is $K(\mathbf{X}, \mathbf{z})$.

This results in an optimal management problem given by

$$\max_{\mathbf{w},\mathbf{X}} \sum_{t=0}^{\infty} \delta^t \left[N\mathbf{z}_t'\mathbf{B}(\mathbf{w}_t, d_t) - K(\mathbf{X}_t, \mathbf{z}_t) \right]$$

subject to

$$d_{t+1} = d_t + \frac{(1-\alpha) N\mathbf{z}'\mathbf{w} - \rho}{\phi} \text{ for } t = 0, ..., \infty$$

$$\mathbf{z}_{t+1} = \mathbf{X}_t \mathbf{z}_t \text{ for } t = 0, ..., \infty$$

$$\sum_{i=1}^{I} x_{ijt} = 1 \text{ for } t = 0, ..., \infty \text{ and } j = 1, .., I$$

$$0 \le w_{it} \le W(d_t, i) \text{ for } t = 0, ..., \infty \text{ and } i = 1, .., I$$

with d_0 and $\mathbf{z}_0$ given. Again, we reformulate this as a dynamic programming problem:

$$V^{OPT}(d, \mathbf{z}) = \max_{\mathbf{w},\mathbf{X}} N\mathbf{z}'\mathbf{B}(\mathbf{w}, d) - K(\mathbf{X}, \mathbf{z}) + \delta V^{OPT}\left(d + \frac{(1-\alpha) N\mathbf{z}'\mathbf{w} - \rho}{\phi}, \mathbf{X}\mathbf{z}\right) \tag{17}$$

subject to

$$w_i \le W(d, i)$$

[9]There is one additional complication to this approach. Since the cost of technology choices varies by farm, we need to retain information about which farms use each technology to correctly compute the cost. In particular, the Nz_i farms currently using technology i have systematically different costs for selecting each of the different technologies for the following period than the Nz_j farms currently using technology j due to both their current technology and the difference in investment costs that led to their different technology states. We assume that, at any point in time, the farms using the most expensive technology are the ones with the lowest investment cost, allowing us to infer the distribution of technology costs among farms currently using technology j from the vector of current technology shares $\mathbf{z}$. As with the state variable shares, each of the I-element column vectors making up $\mathbf{X}$ must sum to 1 implying that the I^2 element matrix is uniquely determined by $I(I-1)$ elements.

and

$$\sum_{i=1}^{I} x_{ijt} = 1.$$

Neither of our problems have closed-form solutions, so we turn to numerical simulation. In the next section, we provide specific functional forms for each of the elements of our model and select parameters for the equations that are reflective of the situation in our study region.

4. Numerical Simulations

Rather than simulating a specific aquifer, we conduct numerical simulations using parameters that are broadly appropriate for western and north-western India, an area that has experienced dramatic groundwater declines (Shah, 2012). We first provide additional structure to the general functions described in our prior model section and then describe how we parameterized these functions.

4.1. **Functional forms.** The annual net benefit of water is computed by subtracting the cost of pumping from the gross benefit of water. We use a linear marginal benefit of water curve until the amount of water needed to fully irrigate a farmer's plot ($\bar{w}$) is reached. Beyond this point, the marginal benefit of water is zero. The true cost of pumping water is linear in depth to groundwater, but in some of our simulations farmers pay only a flat tariff for electricity. Both the marginal benefits and true pumping costs are independent of the well technology, but the flat tariffs vary across technologies. The net benefit function for water is therefore given by

$$B(w,d,s) = \begin{cases} \beta w - \frac{1}{2}\gamma w^2 - w\varepsilon d - \tau(s) & \text{if } w < \bar{w} \\ \beta \bar{w} - \frac{1}{2}\gamma \bar{w}^2 - w\varepsilon d - \tau(s) & \text{if } w \geq \bar{w} \end{cases}$$

where $\tau(s)$ is the technology specific electricity tariff. Under optimal management and a counterfactual common pool simulation, we set ε equal to the estimated true cost of the electricity needed to lift one cubic meter of water one meter and set τ to zero. In the common pool simulations that reflect the current situation in our study area, we set $\varepsilon = 0$ and have non-zero values of τ.

Investment in this region primarily comes in the form of deepening existing wells and purchasing new and more powerful pumps to enable the continued extraction of water as levels fall. The impact of falling water levels on the extraction capacity given a farmer's current technology is captured by our water limit function. We adopt a simple formula for this relationship. Each of our technologies has a maximum depth ($\bar{d_i}$) at which it can extract any water and a maximum depth ($\tilde{d_i}$) at which it can deliver enough water to fully irrigate a farmer's land. Between these two points, water limits fall linearly toward zero as the depth increases to the well's maximum depth. The water limit functions thus have the form

$$W(d,i) = \begin{cases} 0 & \text{if } d \geq \bar{d_i} \\ \bar{w}\left(\frac{\bar{d_i}-d}{\bar{d_i}-\tilde{d_i}}\right) & \text{if } \tilde{d_i} < d < \bar{d_i} \\ \bar{w} & \text{if } d \leq \tilde{d_i}. \end{cases}$$

The cost of investment in our model has two components. First, we identify a baseline level of maintenance expenditures for each technology (denoted by χ_{ii}) and a baseline cost of moving from technology i to technology j (denoted by χ_{ij}). We assume that We assume that farmer heterogeneity scales these costs uniformly, yielding an investment cost function of the form

$$C(j,i,\omega) = \chi_{ij}\omega.$$

The distribution of ω values in the population has probability density function $f(\omega)$ and cumulative distribution function $F(\omega)$. In our simulations, we assume a uniform distribution between 1 and an upper bound Ω. Since the cheaper technologies have lower values of i and we assume that these technologies are employed by the farms with the highest investment costs, we can compute the range of ω values associated with each technology from the shares using each technology. The investment cost function under optimal management is thus given by

$$K(\mathbf{X},\mathbf{z}) = \sum_i \sum_j \chi_{ji} \int_{\omega_{ij}^{LB}(\mathbf{X},\mathbf{z})}^{\omega_{ij}^{UB}(\mathbf{X},\mathbf{z})} \omega f(\omega)\, d\omega$$

where $\omega_{ij}^{UB}(\mathbf{X},\mathbf{z})$ and $\omega_{ij}^{LB}(\mathbf{X},\mathbf{z})$ give the upper and lower bounds of the cost parameter value for the farms switching from technology j to technology i given starting shares $\mathbf{z}$ and investment choice matrix $\mathbf{X}$. [10]

4.2. **Parameterization.** Table I list the values of the parameters used in our baseline simulations; the rest of this subsection explains how we selected these values.

4.2.1. *Benefit of water.* We assume the average farmer has four hectares of land that they plant for three cropping seasons: the rainy season or kharif (June–September), the dry season or rabi (November–February) and the summer summer which is also dry (March–May). The primary crops in this area are rice, pulses and oilseeds. Rice is water-intensive and must be irrigated and can be cultivated in all three seasons. Pulses and oilseeds do not require irrigation but are only grown during the kharif season. We construct a water benefit function reflecting farmers options about which of these crops to grow. Thus our water benefit function captures both the irrigation acreage decision and the crop acreage decision that farmers in this region face. Each season a farmer chooses to grow some fraction of his land with rice. Rice requires 1000 mm of irrigation water during the kharif season and 1500 mm of irrigation water in each of the rabi and summer seasons (Fishman *et al.*, 2015a). Therefore, the maximum volume of water that a farmer will choose to use is 4000 mm of water annually. A farm using 4000 mm of water each year extracts 40,000 m^3 of water per hectare (ha) of land. Evidence suggests that farmers adjust their water usage by reducing acreage planted in rice rather than the reducing the amount of water used per hectare (Fishman *et al.*, 2015b). We estimate that the average, per season net income (exclusive of groundwater costs) from growing rice is 17,000 Rupees (Rs.) per hectare, while the dryland crops earn 4,000 Rs./ha (ICRISAT, 2015).[11] This suggests that marginal benefit of irrigation varies from 13,000 Rs./ha during kharif to 17,000 Rs./ha during rabi and summer. Due to the differing irrigation water needs, this corresponds to 1.3 Rs./m^3 of water during kharif and 1.13 Rs./m^3

[10] The derivation of these bounds is as follows. All farms with $\underline{\omega}_i(\mathbf{z}) < \omega_n \le \bar{\omega}_i(\mathbf{z})$ are currently using technology i. The cutoff values are given by $\bar{\omega}_i(\mathbf{z}) = F\left(\sum_{j<i} z_j\right)$ and $\underline{\omega}_i(\mathbf{z}) = F\left(\sum_{j\le i} z_j\right)$. Using similar logic, we can identify the farms that make each technology choice since upgrading to a technology with a higher index is more expensive. Specifically $\omega_{ij}^{UB}(\mathbf{X},\mathbf{z}) = F\left(\bar{\omega}_j(\mathbf{z}) - z_j \sum_{k<i} x_{kj}\right)$ and $\omega_{ij}^{LB}(\mathbf{X},\mathbf{z}) = F\left(\bar{\omega}_j(\mathbf{z}) - z_j \sum_{k\le i} x_{kj}\right)$.

[11] ICRISAT (2015) gives net revenue numbers which we convert to net income by that assuming net income (exclusive of groundwater costs) is equal to 50% of the net revenue.

during summer and rabi, suggesting a very flat marginal benefit of water curve. These numbers likely understate the importance of at least a minimal amount of irrigation to small subsistence farmers. In our baseline simulations, we varied the marginal benefit of water from 2 Rs./m^3 for the first unit of irrigation water to 1.13 Rs./m^3 at the maximal level of extraction (40,000 m^3/ha). Beyond this level, we set the marginal benefit of water to zero. We conduct comparative statics simulations varying the marginal benefit at either end of the range. We discount benefits and costs at 10% per year.

4.2.2. *Well technologies and costs.* A well technology choice includes both the depth of the well and the horsepower of the associated pump. Groundwater pumps need to be provide appropriate power for the depth of the well. A pump that is too powerful will waste electricity and draw sentiment and other debris into the pump impairing function, while a pump that is too weak will be unable to deliver water to the surface (Kumar Maitra, 2011). We choose to work with three well types to make our numerical simulations tractable and selected these depths to be representative of the range of depths of tubewells in our region (Ministry of Water Resources, 2007). We consider three discrete well technologies with maximum depths of extraction of 25, 50, and 75 meters, respectively, each matched with an appropriately sized pump. In Section 5.3.1, we test the robustness of our results considering simulations with different well technology choices. We assume that each technology can extract enough water to fully irrigate a farmer's land during all three seasons up to a depth of 10, 30 and 60 meters and couple the wells with pumps whose capacity is sufficient to deliver this much water at these depths. Between the upper and lower bound, well capacity declines linearly.

Based on the costs of digging a tubewell and purchasing an electric pump given in Ministry of Water Resources (2007) and Sekhri (2011), we assume that moving from technology 1 to 2 costs between 39,333 Rs./ha to 78,666 Rs./ha for different farmers and moving from technology 2 to 3 costs between 40,000 Rs./ha to 80,000 Rs./ha for different farmers. The cross-farmer variation in investment costs reflects variation in characteristics like wealth, information, credit, and land characteristics. We calibrate the cost of moving from technology 1 to 2, versus the cost of moving from technology 2 to 3, based on an investment cost structure that includes several components.

First, there is a variable cost that depends purely on how many meters the well is deepened. Second, there is a fixed cost associated with any deepening of a well, which includes the costs of getting a rig to the site, transporting materials, flushing the well, and the cost of a borewell cap (India Water Portal, 2009). Lastly, any substantial deepening of a well will require the purchase of a new pump and deeper wells require more powerful pumps, suggesting that there is a component of the cost of deepening a well that is purely a function of the final depth, and is independent of the amount of deepening that occurs.

While it is difficult to precisely estimate the component of the cost of deepening associated with each piece, we scale investment costs to other decisions by assuming the variable charge accounts for 90% of the cost of moving from technology 2 to 3 and the remaining components each represent 5% of the cost. Using these estimates, we conclude that the cost of moving from technology 1 to 2 (an equivalent increase in depth) is 98% of the cost of moving from technology 2 to technology 3, which corresponds to the numbers listed above. Moreover, moving directly from technology 1 to 3 would save 4.2% of the total cost. We set technology 1 to have no annual maintenance costs, and technology 2 to have annual maintenance costs that are equal to 4% of the investment costs (for that farmer) and technology 3 to have annual maintenance costs that are equal to 10% of the investment costs (for that farmer), based on data on annual maintenance costs provided in Ministry of Water Resources (2007). Given the importance of investment costs in our model and the imprecision of these cost estimates, we conduct several comparative static simulations varying different elements of the cost function.

Per unit pumping energy needs are based on the energy required to lift a cubic meter of groundwater one meter and the typical efficiency of groundwater pumps in India.[12] Farmers in this region pay a flat tariff that is a function of the horsepower of their pump. These tariffs are set so that they are linear relative to the monthly pumping capacity of each pump. Based on Badiani & Jessoe (2017), we assume that farmers pay 0.5 Rs. for each kWh of capacity. Thus, a 2 HP pump, with a capacity of roughly 400 kWh per month pays 200 Rs. per month or 2400 Rs./year. Badiani *et al.*

[12]Shah *et al.* (2006) estimate that the typical groundwater pump in India has a pumping efficiency of roughly 25%.

(2012) note that the 0.5 Rs./kWh is roughly 15% of the actual cost of electricity, implying an actual electricity cost of 3.3 Rs./kWh.

4.2.3. *Aquifer parameters.* The state equation for the evolution of groundwater levels requires three parameters: the return flow coefficient, the annual inflow of water, and the aquifer storativity. The return flow coefficient measures the share of extracted groundwater that returns to the aquifer. We use a value of 25% for this parameter, based on a reported range of 20% to 35% in Ministry of Water Resources (2009). The annual inflow (or recharge) is the amount of water, exclusive of return flow, that flows into the aquifer each year. We set this number relative to the maximum consumptive use in the region. Since 25% of the 40,000 m^3 applied to a fully irrigated ha returns to the aquifer, maximum consumptive use is 30,000 m^3/ha. We note that the average level of groundwater development—measured as the ratio of current usage to annual recharge—is about 150% in our study area (Suhag, 2016). In addition, currently roughly 50% of the sown area is irrigated with groundwater (Fishman *et al.*, 2016). This indicates that if all sown land was irrigated then water usage would be 300% of annual recharge. Hence, we parameterize annual recharge to be 10,000 m^3/ha, or roughly 1/3 of the maximum consumptive use. To parameterize aquifer storativity, we use an inductive approach. Groundwater levels have been dropping as much as 3 meters per year with current extraction (Fishman *et al.*, 2015b). We infer a storativity value by assuming that if all farmers in the region fully irrigated their land every year, water levels would drop 3m each year.

5. RESULTS

5.1. **Baseline Simulations.** The results of our initial simulations are illustrated in Figures 1, 2, and 3. Figure 1 illustrates the water level and associated pumping cost in each of our three scenarios. The dotted horizontal lines in the figure identify the maximum depth of well types 1 and 2 and the maximum depth at which pumping yields a positive instantaneous social net benefit (e.g. the point at which pumping cost exceeds the intercept of the marginal benefit curve). Figure 2 illustrates water use in the region over time. The height of the top line in each panel illustrates the weighted average water extraction per ha with the colors indicating how much water was extracted by each technology. Since we set the marginal benefit of water to zero beyond 40,000 m^3/ha, water use never exceeds this level. Finally, Figure 3 presents the cumulative present value of costs and net benefits in each case. The height of the top line in each panel illustrates the present value of gross benefits received up until that date. The shading breaks the gross benefit down into investment costs, energy costs and net benefits. Social net benefits are shaded in dark blue, energy costs are shaded orange and investment costs are shaded red. The cross-hatching in the flat tariff panel represents the energy cost subsidy, so the net benefits received by farmers in this panel are the sum of the social net benefit (in dark blue) and the energy cost subsidies (in the cross-hatched orange region).

Given the parameters described in the previous section, the sustainable steady-state level of water use is an average of 13,333 m^3/ha in all three scenarios. Thus, we see water extraction stabilizing at this level in all three scenarios. Note that 25% of this water returns to the aquifer, resulting in consumptive use of 10,000 m^3/ha. At this level of water use, the marginal value of water is 1710 Rs./m^3 and the total annual benefit of irrigation before water costs is 24,733 Rs./ha.

Under the flat tariffs that generally prevail in the region, we see repeated waves of investment in technologies that allow farmers to extract water from farther below surface. In this scenario, the water level drops rapidly from an initial pumping lift of 2m to just below 10m. At 10m, the volume of water that can be pumped from type 1 wells begins to decline and, as a result, water use drops briefly, as illustrated in the top panel of Figure 2. However, farms rapidly invest in deeper wells to restore their ability to fully irrigate their land and total water use is quickly restored to the same level and water levels continue to decline. The same pattern repeats when type 2 wells begin to fail. Given the high discount rate, farmers delay investment for a few years, but eventually, we see a second rapid wave of investment in technology 3.[13] Since our model includes only three technologies, we do not see a third wave of investment when technology 3 begins to fail. Instead, as technology 3 begins to fail, farmers' ability to extract water falls. We eventually reach a steady state when the reduced extraction capacity of wells limits overall consumptive extraction to the annual

[13]Note that although farmers in our model have the option to invest in type 3 wells immediately, they do not do so. Our parameterization suggests that farms would save roughly 4% of the total investment cost by making a single transition, but given the discount rate, farms save more by delaying the second investment.

recharge level. As we demonstrate in Section 5.3.1, when we include the option to investment in another technology, we see continued investment.

In the steady-state with flat tariffs, water levels stabilize at 70m below the surface, as shown in Figure 1. At this depth, the actual cost of pumping water to the surface is just over 2500 Rs./m^3, which exceeds the marginal benefit of water. This result is consistent with studies of the region that suggest that if farmers were paying the full cost of their electricity use, profits would be negative (Lall *et al.*, 2011). However, under flat tariffs, farmers with type 3 wells pay an annual tariff of only 6000 Rs./ha for electricity. From the perspective of farmers, the steady-state annual profit net of water and well maintenance costs is 5600 Rs./ha. However, from the points of view of society, irrigation is costing the region almost 15,000 Rs./ha each year. This divergence can be seen as accumulated social net benefits (the blue area) in the top panel of Figure 3 fall toward the limiting value while the accumulated farm benefits (the sum of the blue and cross-hatched orange areas) in the same panel rise to the limiting value.

The optimal management scenario is starkly different. Since water extractions in the steady-state are limited to 13,333 m^3/ha, the benevolent dictator seeks to keep the cost of extracting that water low. Consistent with the descriptions of the region, investment in new technologies is inherently wasteful from a social perspective. The new wells do not increase the sustainable water extraction capacity; they merely enable farms to extract the same water from deeper depths. Thus, the investment increases the cost of farming twice: water costs more to extract, and the investment cost itself is wasteful. The optimal management scenario sharply curtails pumping on individual farms. Water levels are allowed to drop to 20m since type 1 wells can extract the sustainable level of 13,333 m^3/ha from this depth. Farms have the same marginal value of water (roughly 1710 Rs./m^3) but the cost of water extraction is only 720 Rs./m^3. Instead of losing roughly 15,000 Rs./ha each year in the steady-state, society gains approximately 15,000 Rs./ha annually. Accumulated social net benefits thus rise to the limiting value in the bottom panel of Figure 3.

Given this stark contrast, we see that optimal management would increase the net social benefit of irrigation in the region by 66%. The common pool scenario with flat tariffs yields higher profits in the early years, but this advantage is quickly reversed. However, from the perspective of farmers, the situation is different. Since they are paying a small portion of their energy costs, farmers themselves are roughly 10% worse off under the optimal management scenario than they are in the common pool scenario with flat tariffs.[14]

It is apparent from these results that the heavy subsidization and flat electricity tariffs contribute substantially to the losses caused by the current situation. We conducted a second set of common pool simulations designed to isolate the common pool externality from the loss due to the distortionary subsidies. In these simulations, we considered the behavior of farmers facing the actual marginal cost of electricity but no regulatory limitations on water usage. This scenario looks fairly similar to the flat tariff scenario for the first 15 years. Water levels drop rapidly, and as type 1 wells begin to fail, farmers transition to type 2. When type 2 wells begin to fail at around 30m of depth, farmers now face considerably higher pumping costs. In the steady-state, water is just over 43m below surface and costs just under 1560 Rs./m^3 to pump to the surface. The marginal benefit of water exceeds the marginal cost by a small amount, but farms are limited by the extraction capacity of their wells and do not find it worth the cost of investing in a type 3 well for a small gain in benefit.

Farmers faced with the real cost of electricity will thus avoid the second wave of well deepening. This increases the total social gain relative to flat tariffs by roughly 35%. As a first approximation, we thus find that just over half the gains from optimal management are due to the eliminating the effect of the distortionary subsidies. The common pool problem remains critical, however. We find that even in a scenario where farmers are charged the true cost of electricity, implementing optimal management will increase the aggregate benefit of irrigation by nearly 23%. Moreover, in many ways, this percentage understates the true importance of addressing the common pool externality. As we see in Figure 1, the path of water levels for the first several years is quite similar among the three scenarios. While it would be optimal to limit extraction from type 1 wells in the early years to some degree, the real divergence occurs as type 1 wells begin to fail. This suggests that

[14]Note that this does not suggest that the common pool outcome maximizes the benefits to farmers under flat tariffs. To find the optimal outcome from the farmers' perspective, taking the flat tariffs as given, would require solving a different dynamic optimization problem. It would, however, be cheaper for the government to implement the optimal management solution we identify and to compensate farmers for their loss than it would be to impose this "pseudo-optimal" solution.

implementing optimal management may not be critical immediately, but increases in importance as type 1 wells begin to fail. To assess this conjecture, we computed the impact of imposing optimal management just as type 1 wells begin to fail. While waiting this long lowers the overall social benefits, the percentage gain from that point forward increases to 54% using the real energy cost and to over 400% using the flat tariffs.

5.2. **Comparative Statics.** We conduct a series of comparative static simulations to test the sensitivity of our results to the value of the parameters that we used. Table II presents the resulting percentage gains from imposing optimal management under various parameter values, while Figure 4 illustrates the impacts on various outcome variables. In the figure, the first group of three bars illustrates the outcome in our baseline scenario for each of the three management scenarios. The remaining groups illustrate the outcomes for each of our comparative static scenarios. The dashed horizontal lines are drawn at the height of the three baseline bars to facilitate comparisons across the different scenarios.[15]

5.2.1. *Changes in investment costs.* One of the striking conclusions of our baseline scenario is that, despite the variation in investment costs, all farms make essentially the same decisions about investment. There is variation in the timing of each move, because the lower cost farms will invest at a lower threshold than the high cost farms. But, with the investment cost distribution above, all farms eventually invest in technology 2 in both common pool scenarios. Similarly, all farms invest in technology 3 if facing flat tariffs but none invest if facing real energy prices. We conducted a series of additional simulations in which we varied the cost of investment. In our baseline scenario, we assume that moving from technology 2 to 3 costs farmers between 40,000 Rs./ha to 80,000 Rs./ha, with the variation depending on farmer characteristics like wealth, information, credit, and land characteristics. We conducted simulations for four variations: (a) lowering the minimum investment cost from 40,000 Rs./ha to 30,000 Rs./ha, (b) raising the minimum investment cost to

[15]The horizontal lines are absent on the graph depicting the share irrigating since everyone is irrigating in the steady-state in the baseline scenario. Moreover, since investment never occurs under optimal management, there are only two horizontal lines and two bars on the present value of investment and maintenance graph.

50,000 Rs./ha, (c) lowering the maximum investment cost from 80,000 Rs./ha to 60,000 Rs./ha, and (d) raising the maximum investment cost to 100,000 Rs./ha.[16]

The first three simulations have only small impacts on the outcome. The timing of choices varies slightly, but the essential character of the solution remains unchanged. In these cases, changing investment costs has no impact on the net present value of irrigation under optimal management (since investment never occurs). Moreover, since investment follows essentially the same pattern as in the base case, revenues and pumping expenditures remain almost unchanged in the common pool cases. Changing investment costs does have a small impact on the present value of investment expenditures, with higher investment costs leading to larger costs. These larger costs lower the net present value of irrigation. The percentage gains from optimal management increase because the numerator (the level of gains) increases and because the denominator (the common pool net benefits) falls.

The final simulation, raising the maximum investment cost to 100,000 Rs./ha, has a similar impact as the previous three under flat tariffs. In contrast, in the common pool scenario with real energy costs, we now see some farms shift to dryland crops or exit agriculture, instead of investing in deeper wells. For this particular value, 10% of the farms elect to exit agriculture. Since the remaining farms pump more in the steady-state as a result, this change has a minimal effect on revenues, lowering the present value by just over 2%. At the same time, this exit reduces steady state pumping lifts by about 1m and decreases the present value of all pumping expenditures by about 4.25%. More importantly, it reduces the present value of investment expenditures by about 14% relative to the baseline. The combined effect is to increase the net present value of irrigation benefits by just under 2% and to reduce the percentage gain from optimal management from 23% to 20%. We thus find a non-monotonic effect of increasing investment cost on the percentage gains from management. Increasing investment costs increases the gains from optimal management until we move into a region where farms begin electing to exit agriculture. Further increases in investment cost beyond this threshold will tend to reduce socially wasteful investment in deeper

[16] In our baseline simulation, we assume that moving from technology 1 to 2 costs 98% of this amount that it costs to move from technology 2 to 3. For this set of comparative statics, we assume that the cost of moving from technology 1 to 2 is always 98% of whatever it costs to move from technology 2 to 3.

well technology and therefore reduce the gains from imposing optimal management. However, while the percentage gains are lower in these cases, we have more reason to be concerned about equity in the outcome, since increasing numbers of farms are driven out of irrigated agriculture.

5.2.2. *Lower discount rate.* Our baseline simulations used a discount rate of 10%, which is relatively high compared to most studies of the Gisser-Sanchez effect. Given the developing country context, we believe that the 10% discount rate is appropriate, but this choice may significantly influence the estimated results, as Brill & Burness (1994) demonstrate. We conducted another set of simulations using a discount rate of 5%. The lower discount rate substantially increases the estimated gains to management for two reasons. First, under optimal management, the higher weight placed on future benefits leads to lower pumping today and higher steady-state water levels (and therefore lower steady-state pumping costs), while steady-state water levels remain virtually unchanged in the common pool scenarios. Second, the large difference between gains in the future and the investment expenses weighs more heavily in the comparison between scenarios, since they are not discounted as heavily. As a result, we find that optimal management would increase net benefits by over 465% if farmers are facing flat tariffs, and by 60% if they are facing real marginal energy prices.[17]

5.2.3. *Changes in the marginal benefit of water.* Because we have chosen to use a reduced form water benefit function that subsumes many other annual choices, we conduct comparative statics on the specific parameters and describe qualitatively what these results suggest about the embedded choices. Our baseline simulations used a marginal benefit of water that starts at 2 Rs./ha, falls linearly to 1.13 Rs./ha at 40,000 m^3/ha, and then drops discontinuously to 0 at any higher level. We conducted additional simulations in which we lowered each of these values. Reducing the initial marginal benefit (choke price) corresponds to rotating the marginal benefit curve downward around the value at the maximum water use level. One real world change that could lead to this shift would

[17]Although it is not apparent in our main comparison, there is a third way that lowering the discount rate can increase the estimated gains. We conducted another comparative static simulation in which we lowered the discount rate for our high maximum investment cost scenario. In this simulation, the lower discount rate increases farms' incentive to invest in the real marginal energy cost scenario. Instead of 90% of the farms choosing to invest in technology 2, 96% of farms do. The lower discount rate thus reduces the rate at which increasing investment costs will slow investment and reduce the gains from management.

be the introduction of higher value dryland crops and/or increases in the price of such crops. The reduction in the choke price impacts our estimates in three ways. First, it lowers the benefit of water at every point, reducing the net present value of irrigation in all of the simulations. Second, this lower benefit leads farmers to reduce consumption faster and reduces steady state pumping lifts. Third, it reduces the number of farms irrigating. Under real energy prices, only 53% of farms ever invest in type 2 wells, and just over 14% of farms invest in type 2 wells but eventually abandon them to avoid continued maintenance costs on wells that produce less water. The reduced investment substantially lowers the present value of investment expenditures and, therefore, reduces the percentage gain from optimal management to roughly 18%. Under flat tariffs, all farms still invest in type 2 wells and then type 3 wells. However, almost 21% of the farms abandon the type 3 wells as yields fall (but before they run dry) because the volume of water that can be pumped is insufficient to justify the costs of well maintenance and the flat tariff. Since the investment is still incurred, we do not observe the mitigating effect of reduced investment, and percentage gains increase to over 255%. In contrast, a high choke price suggests a substantial marginal value of the first units of irrigation. Results from our simulations with a high choke price can thus shed light on the consequences of reduced irrigation on crop prices. If irrigation falls across the region, the price of rice might rise due to general equilibrium effects, indicating a much higher value of the first units of water than would be estimated holding rice prices constant.[18] Our results suggest that this would lead to higher estimates of the gains from imposing management relative to true marginal electricity pricing and a lower estimate of the gains from imposing management relative to flat tariffs.

We also conduct a simulation lowering the marginal benefit at the maximum level, which corresponds to increasing the slope of the marginal benefit curve while keeping its vertical intercept unchanged. This similarly reduces the benefit of water at every point, reducing the net present value of irrigation in every simulation. However, since it is well capacity limits and the maximum water needed for fully irrigating a field that tend to determine farmers' water use, this change has

[18]Note that while it would be possible to define a water benefit function incorporating general equilibrium effects suitable for use in the optimal management problem, this would not be viable for the common pool problem. Farmers would properly take the price of the crops as given when making decisions but then form expectations about the price based on their assumptions about neighbors responses.

minimal impact on farmers' water use. Steady-state levels, and thus the present value of pumping expenditures, remain virtually unchanged. Under flat tariffs, the change has no effect on investment and increases the percentage gains from management to106%. In contrast, under real energy prices, the reduced benefit of water reduces the incentives for farms to invest, and 9% of farms exit irrigation rather than invest in type 2 wells. While reduced investment tends to lower the gain to management, the net effect of the changes is still positive, with percentage gains increasing from nearly 23% to nearly 26%.

5.2.4. *Changes in aquifer characteristics.* As the Gisser-Sanchez literature makes clear, the specific characteristics of a region's aquifer can have a substantial impact on the results. Our baseline simulations set the natural recharge rate and aquifer storativity based on the maximum consumptive use in the region. Since individual parts of our region of interest have different hydrological characteristics, we explored the sensitivity of our results to changes in the aquifer parameters. Our baseline simulations set natural recharge at one-third of the maximum annual consumptive use in the region and storativity by assuming that if all farmers fully irrigated their land each year (thus using three times the natural inflow), water levels would drop 3m each year.

We first conducted a simulation where the annual drop rate was reduced to 2m per year, corresponding to an increase in the storativity of the aquifer. This has no significant impact on the eventual steady-state levels but increases the time it takes to get there and the amount of water extracted along the way. The extra extraction increases the present value of benefits in every case and decreases the present value of pumping expenditures (because the high pumping costs occur later and more water is extracted from shallower depths). Moreover, it pushes investment forward lowering the present value of those expenditures. The net effect is to reduce percentage gains substantially to 24% with flat tariffs and just under 10% with real energy costs. Note, however, that if we compute percentage gains just before the first wave of investment would begin, the percentage gains would increase to almost 97% with flat tariffs and 24% with real energy costs.

We also conducted a simulation where steady-state recharge was increased to half of the maximum annual consumptive use, while the annual drop in response to full irrigation was held constant. Since the annual drop is a function of the difference between extraction and recharge, increasing recharge and holding the annual change constant implies decreasing the storativity of the aquifer since a smaller amount of over-extraction is lowering water levels by the same amount. This combined change increases the steady-state water consumption and raises the steady-state water level. Since steady-state water consumption goes up, gross benefits increase in all cases, although the increase is largest under optimal management. The reduced pumping depths mean that per unit pumping expenditures are smaller but since more water is being pumped, total expenditures on pumping increase in the two common pool scenarios. The net effect is to increase percentage gains from optimal management to almost 88% relative to flat tariffs and 35% relative to real energy costs.

5.3. **Model Variations.** We also test the sensitivity of our results to two variations to our model. First, we analyze how our results change if we consider a more flexible set of well technologies. Second, we analyze how our results change if farmers have adaptive expectations over future groundwater depths instead of rational expectations as in our baseline scenario.

5.3.1. *Variations in Available Well Technologies.* Our baseline simulations include three different well technologies. We limited farmers to three choices to address the curse of dimensionality in solving the optimal management problem. As we note in Section 3.4, the dimension of our state space is the same as the number of available technologies and the optimal management problem proved numerically intractable with more than 3 dimensions. Still, allowing only three technologies is a substantial simplification and understanding the impact of this assumption is critical. We adopt two distinct approaches to investigate how robust our finding of significant benefits of management is to this choice.

First, we note that while the social planner in our optimal management problem has three technologies to consider in our baseline scenario, the social planner uses only the first technology. As a result, the net present value we compute in our baseline simulations is a lower bound; regardless of what technologies we make available, the social planner would maintain the option to never invest and obtain the benefits we identify. However, our baseline simulations cannot determine whether the social planner could obtain higher benefits by investing in better well technology on some farms if we offered the option to deepen wells by less than 25m. We thus explore the implications of maintaining three technologies but reducing the depths of the latter two options. To do this, we solve the optimal management problem with three different sets of maximum well depths: $\{25,30,35\}$, $\{25,35,45\}$, and $\{25,45,65\}$. In all cases, the optimal management solution remains no investment and there is no change in the net present value of implementing the optimal management solution.[19] These results suggest that limiting the options available to the social planner did not materially change the character of the optimal management solution.

Second, we note that the curse of dimensionality is substantially greater for our optimal management problem than it is for the common pool problem. In the optimal management problem, we solve a dynamic optimization with I state variables, while in our common pool problem, we solve a dynamic optimization problem with two state variables, one of which can take on I discrete values. Increasing I is far less costly in this case. Our model can be solved in a reasonable time frame as long as we keep the number of available technologies under 10. We therefore solve the common pool problem under both cost structures with much finer technology increments. Our original specification limited farmers choices in two key ways. First, we forced farmers to make relatively large increases in well depth. Second, we artificially limited the maximum depths wells could reach. By introducing new well options, we can identify the impacts of both restrictions. As one would expect, offering different options does change the specific common pool solutions.

For the flat tariff common pool scenario, we first offer farmers a set of technologies corresponding to maximum well depths ranging from 25m to 75m in 10m increments instead of our baseline 25m increments to address the concern that the large depth increments artificially influenced our results. This change slightly increases the gains from imposing optimal management. The net social benefits of the common pool solution fall from just under 204,000 Rs./ha to just under 202,000

[19]As we make the well increments shorter, the model solution becomes less stable and more sensitive to starting points. In particular, our algorithm sometimes identifies a solution in which deepening some of the wells at least once appears optimal, depending on the algorithm's starting point. Closer investigation reveals that these are local optima as the no investment solution identified in our baseline yields a slightly higher net present value.

Rs/.ha, increasing the gains from imposing optimal management to 67.5%.[20] We then turn to the second consequence of our technology restrictions and offer farmers the option to continue deepening their wells by considering maximum well depths ranging from 25m to 115m in 10m increments. When offered the option, most farmers elect to continue deepening their wells. Net social benefits fall to just under 140,000 Rs./ha and gains from management increase to roughly 142%. By the last year of simulation, just over 35% of farms have exited agriculture, but the remaining 65% are still artificially constrained from deepening their wells further. If we could feasibly increase the number of technologies to allow further deepening, the investment cycle would continue, further lowering the net social benefit in the common pool simulation.[21] We thus find that artificially limiting the number of technologies available in the common pool scenario to three widely spaced wells underestimated the degree of the common pool problem with flat tariffs.

For the real marginal cost common pool scenario, we considered 7 well technologies with the maximum depths ranging from 25m to 55m in 5m increments. In this scenario, we find two changes. First, as with the flat tariff results, farmers take longer to reach a given depth. Second, while all of the farmers eventually deepened their wells to 50m in the baseline scenario, we find that 27% of the farmers will choose to deepen wells until they reach 45m but will elect to exit agriculture rather than deepen their wells to 50m, while the remaining 73% will stop at 50m rather than continue to 55m. None of the farmers elect to deepen wells further than 50m. Combining both effects increases net present value of social benefits from 276,000 to 289,000 Rs/ha, lowering the percentage gains from optimal management to roughly 17%. Because no farmers elect to deepen wells further than 50m, our original technology options do not artificially constrain the maximum depth but do overstate the pace and thus the cost of investment. Still, our more detailed

[20] While the 10m increments are substantially more granular than the baseline simulations, they still restrict farmers' options. We are unable to numerically solve our model with finer well increments while maintaining a maximum depth of 75m, but we also consider a scenario with 5m depth increments with a maximum depth of 65m. In this simulation, we find that both artificially constraining the investment cycle to end at 65m and using a finer grid of options increases the social benefit under the common pool scenario. Net social benefits rise to roughly 228,000 Rs./ha and the gains from imposing optimal management fall to 48%. Still, we note that the accumulated benefits under our baseline scenario and this modified scenario track quite closely until we reach the artificial limit at 65m. Moreover, we note that when 5m increments are offered, we begin to observe leap-frogging behavior where some farms elect to deepen their wells by 10m rather than 5m to save on fixed costs.

[21] Additional simulations with larger well increments and deeper maximum depths confirm this fact.

results confirm the existence of substantial gains from imposing optimal management compared to a common pool problem in which farmers have the option to invest to overcome capacity limits.

While our simulations are necessarily approximations, we believe they track real world patterns of investment better than continual small adjustments. Perveen *et al.* (2012) report that over a 10 year period, 10% of farmers didn't deepen their well, 35% of farmers deepened their well once, 35% of farmers deepened their well twice, and 20% deepened their well three times or more. In contrast, in our baseline scenario, we observe one wave of deepening in years 5 and 6 (under both flat tariffs and real marginal cost pricing) and a second wave of deepening 8-9 years later (in years 13 and 14) with flat tariffs. When we offer finer increments, the pattern depends on the pricing structure. With real marginal cost pricing and 5m increments available, we observe a wave of deepening in years 3-4, a second wave in years 8-10 in which a small number of farms invest twice and most leap-frog technologies, a third wave whose timing occurs between 10 and 20 years later depending on the farm's cost.[22] With flat tariffs and 10m increments available, we observe waves of deepening every 3-4 years. With flat tariffs and 5m increments, we again observe waves roughly every 3-4 years. In each of these waves, most farms leap-frog technologies and deepen their wells by 10m, while some invest twice. While our results do not match the observed investment patterns exactly, they show a broadly similar outcome: farmers invest regularly, but not every year.

Finally, we conduct an additional series of simulations where we consider multiple technologies and consider different shares of the investment costs that are fixed and the portion that depend on the depth of the final well, irrespective of starting point. We consider values of 2.5%, 5%, and 10% for each of the costs. The variation has little impact on our results. Under flat tariffs, lower fixed costs are associated with marginally smaller , but still quite large, gains from optimal management. When we assume the fixed portion of the cost is only 2.5% instead of 5%, the gain from imposing optimal management when considering 10m well increments up to 115m falls from 125% to 121%. In contrast, under real marginal cost pricing, lower fixed costs are associated with slightly higher gains from imposing optimal management because more farms ultimately invest in 50m deep wells and associated pumps. Percentage gains increase from 17.12% to 17.45%.

[22]Some farms elect to exit agriculture instead of deepening their wells in this wave.

5.3.2. *Adaptive Expectations About Water Levels.* Under an optimal management regime, both groundwater pumping and well investment decisions are made in a dynamically optimal manner. In our baseline simulations, we compare this regime to an unregulated common pool regime in which individual farmers behave "myopically" with respect to the impact of their pumping on future groundwater levels, but make dynamic decisions about well investment based on rational expectations about future groundwater levels. If instead farmers do not anticipate future drops, but expect water levels to remain at their currently level indefinitely and adapt this expectation each year, the investment problem changes.

We conduct an additional set of simulations in which farmers believe water levels will remain constant at their current level indefinitely and only invest in a deeper well technology if it makes sense to do under that assumption. We find that adaptive expectations make the common pool scenario less damaging. Instead of proactively deepening their wells in anticipation of water levels falling as their neighbors also deepen wells, farmers wait to invest until levels actually fall. Since investment is socially wasteful, this delay is beneficial. It reduces the benefits of optimal management, but the impact is relatively small. If farmers facing flat electricity tariffs make investment decisions "myopically" in this fashion, the rate of investment slows down relative to our baseline rational expectations model. Instead of all farms adopting technology 3 within 14 years, it takes 16 years in the myopic case. This slower investment increases the social benefits of the common pool scenario roughly 7% and reduces the gain from imposing optimal management from 66% to 55%. Similarly, if farmers facing real marginal cost pricing make myopic investment decisions, it takes farms 8 years instead of 6 to fully adopt technology 2, increasing the social benefits of the common pool scenario roughly 3% and reduces the gain from imposing optimal management from 23% to 19%. Taken together, these estimates suggest that our results are robust to scenarios under which farmers have either rational expectations or adaptive expectations about future groundwater levels.

6. Discussion

Our results demonstrate substantial losses associated with the common pool regime. The results are consistent with widespread concern about groundwater over-extraction in India. Understanding the issue of groundwater sustainability in India is especially critical in the context of climate change, which may lead to more erratic rainfall and increased demands on groundwater usage as farmers adapt to new rainfall patterns (Shah, 2009; Zaveri *et al.*, 2016; Fishman, 2016; Taraz, 2017). Policies that have been suggested to address groundwater over-extraction include changing the electricity price; rationing water use with fixed quantitative ceilings on water and electricity per hectare (Suhag, 2016); instituting local regulations on drilling depth and the distance between wells; and encouraging farmers to switch crops or adopt precision irrigation technologies.

We leave detailed analysis of these remaining policies to future work, but note that our work casts helpful light on some of the options. Our results highlight the importance of electricity pricing and suggest that moving to full cost electricity pricing would reduce the common pool externality significantly, but would not eliminate the problems, especially in regions that have yet to experience substantial well deepening. We do not explicitly simulate the impact of making this shift after several waves of well deepening have occurred, but our results indicate that doing so would dramatically reduce pumping. We find that well depths are driven below the maximum economic depth for pumping. Each successive year at the steady-state in our common pool, flat tariff scenario produces societal losses. If farmers paid the full cost of electricity, they would cease to pump groundwater. This reality has been noted by previous authors and underlies strong political pressure from farmer groups to maintain the subsidized flat tariffs.

In principle, charging farmers *more* than the true cost of electricity could help mitigate the remaining common pool problem. We conduct an additional series of simulations to explore this possibility, first increasing the size of the flat tariffs and then implementing a volumetric charge at rates above the true marginal cost. If the rates are high enough, either approach could effectively deter investment in deeper wells and thus eliminate most of the common pool externality. However, doing so would require large increases in electricity costs for farmers. We find that it would require a tariff on type 2 pumps of nearly 5.3 times the current tariff coupled with a tariff on type 3 pumps nearly 2.2 times as high as the current tariff to prevent investment and achieve close to the social optimum levels of water usage and irrigation investment. Similarly, we find that the government would need to set volumetric tariffs at roughly 1.7 times the true marginal cost to eliminate investment.[23] Given the lack of political will to move to true cost pricing, it is highly unlikely that these large increases would be politically viable in India at this time.

An alternate approach would be to place fixed limits on the amount of water and/or electricity that can be used on a hectare of land. In our model, time-varying limits on either water or electricity could be used to implement the optimal management solution we identify, since we only consider farmer heterogeneity with respect to investment cost. In a more detailed model with cross-farmer heterogeneity in the water benefit function, uniform limits would likely be able to capture much, but not all, of the potential gains from optimal management. There are also calls to place limits on drilling or deepening wells. Since our results suggest that much of the common pool problem is related to investment, limits on drilling or deepening wells could prevent future waves of well deepening. This is especially important given our results in Section 5.3.1, which suggest that well deepening would likely continue on beyond 75m if the option is available.[24]

Since decisions about crop choice are embedded in our water benefit function, we cannot directly assess the impact of encouraging farmers to change crops. However, our results do suggest that lowering the marginal benefit of the first units of water—by discouraging rice cultivation and/or increasing the return to less water intensive crops—could substantially reduce the common pool losses, if coupled with marginal cost electricity pricing.

The Indian government has also adopted policies to promote more efficient irrigation technologies (Sekhri, 2013; Fishman *et al.*, 2016). To fully model the impact of irrigation technology, our model would require an additional set of state variables (the current irrigation technology in use

[23]The increased electricity prices in both scenarios serve to help internalize the user cost of water. Note however that neither constant price can appropriately reflect the time varying user cost of water. Hence, while either regime can replicate the socially optimal investment trajectory (no investment), neither can exactly replicate the socially optimal pumping path. Moreover, note that pursuing this policy would only be beneficial if the government uses the surplus revenue from electricity in socially beneficial ways. Farmers in the region would be worse off under either policy unless the surplus revenue was returned to them in a lump-sum fashion.

[24]Observers also often suggest restrictions on the distance between wells. The spatially explicit model in Brozović *et al.* (2010) suggests such restrictions may be helpful. Our model and data do not provide enough detail about the spatial distribution of wells in the region to assess how successful such a policy would be.

on each farm), rendering the model intractable. An intermediate option would be to add a third control variable, allowing farmers to make instantaneous adjustments to their irrigation technology. Although it would simplify the dynamics of the irrigation technology investment decision, this approach would shed light on a critical tension in these irrigation technology policies: improved irrigation technology lowers the amount of water applied to crops but has a much smaller impact on the amount of water consumed by the crops. In our study region, roughly 25% of the water applied to crops eventually returns to the aquifer and our steady-state water consumption is determined by a limit on the consumptive use of water. Precision irrigation technology would reduce the amount of water extracted but would not change the steady level of consumptive use. Moreover, the lower marginal cost of extraction can lead to an expansion of irrigated acreage that ultimately lead to an increase in the consumptive use from the aquifer (Pfeiffer & Lin, 2012, 2014a; Fishman *et al.*, 2015a). How these tradeoffs would play out in our context is uncertain. Unfortunately, we do not have sufficient data on the costs of such technologies in India or on how these technologies would affect return flows in the region versus the fraction of the applied water that is lost due to evapotranspiration. Moreover, usage of these technologies in India is currently very low, with roughly 2% of areas irrigated with drip irrigation and 3% of areas irrigated with sprinkler irrigation (Narayanamoorthy, 2006). This low usage number suggests that their are either financial barriers or non-financial barriers, which include the high capital cost of the system, lack of suitability for marginal and small farmers following subsistence farming and the lack of incentives to adopt these costly technologies due to subsidized flat rate electricity tariffs and low marginal groundwater extraction costs (Narayanamoorthy, 2006).

7. Conclusions

There are widespread concerns about the rapid depletion of groundwater in India, which has potentially catastrophic negative impacts on food security and poverty (Sekhri, 2014). We update the canonical groundwater common pool resource model to incorporate key features relevant for India: low marginal extraction costs due to highly subsidized flat rate electricity tariffs; well capacity constraints based on groundwater depth; and endogenous well investment to overcome these constraints. Numerical simulations of our model suggest substantial societal losses due to groundwater over-extraction and excessive investment in well-deepening: optimal management would increase the net social benefit of irrigation in our study region by 66% relative to the scenario of common pool groundwater use and flat electricity tariffs. Even under a common pool scenario where farmers pay the full marginal costs of electricity, we still find gains to optimal management of almost 23%, an estimate that is much higher than many existing studies of groundwater management gains.

Previous work has documented the impact of electricity subsidies on increased pumping, but we add critically to the literature by explicitly linking three market failures—an electricity cost subsidy, a pumping cost externality, and an entry/investment cost externality—in a framework that provides numerical estimates of the potential gains from management. These market failures are reinforcing in that the problems associated with each externality compounds the others. For instance, while Badiani & Jessoe (2017) find relatively small deadweight losses from the electricity subsidies in a static framework, we find that these subsidies substantially increase the common pool externality by increasing investment in deeper wells that are socially wasteful. Although there is some variation in the magnitudes, our finding of substantial societal losses is robust to a variety of changes in the fundamental parameters of our model. In addition to efficiency losses, under some parameter scenarios we also find equity issues. Specifically, as investment costs rise or benefits fall, some farms are driven out of irrigated agriculture—either shifting towards dryland agriculture, exiting from agriculture, or migrating out of the region—consistent with results found by other researchers (Fishman *et al.*, 2015b).

Our analysis focused on a particular region in India that has already experienced severe declines in groundwater levels with accompanying substantial investments in well-deepening, but our work is also relevant to other regions that are at earlier points in their groundwater development. Roy & Shah (2002) describe a common path of groundwater use in numerous regions as moving "from a stage where [an] underutilized groundwater resource becomes instrumental in unleashing [an] agrarian boom to one in which, unable to apply brakes in time, the region goes overboard in exploiting its groundwater resources." Our work illustrates the critical role that investment in deeper wells can play in driving this cycle, especially when government policies exacerbate, rather than dampen the natural challenge. In many regions, governments have initially subsidized investments in groundwater irrigation hoping to trigger expansion of irrigation and reductions in poverty. If these subsidies are not removed once irrigation takes off, they can quickly become pathological and lead individual users to compete away all or most of the gains from irrigation in a competitive drilling and deepening race. Our results thus indicate the importance of caution as new regions like eastern India seek to expand groundwater irrigation.

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FIGURES

FIGURE 1. Water levels

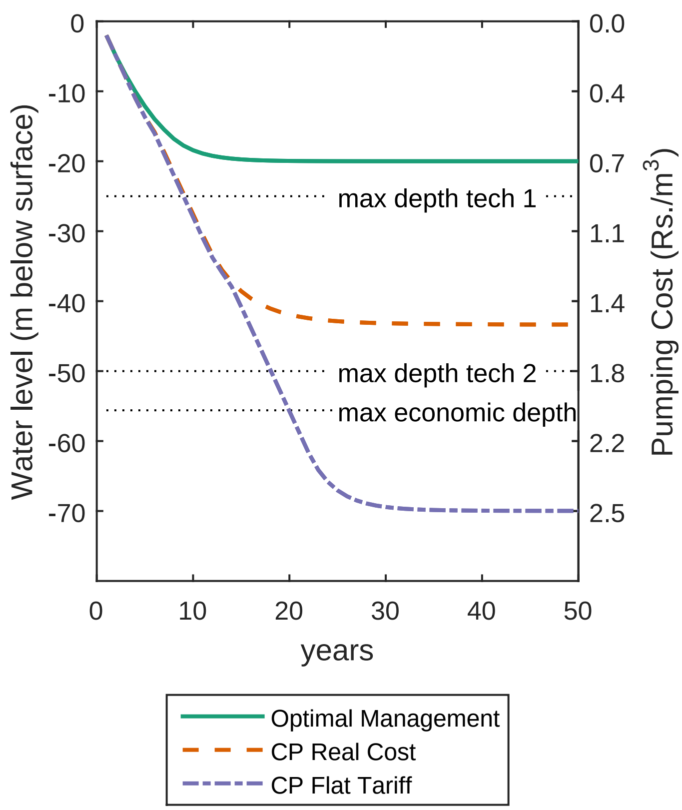


FIGURE 2. Water Use Over Time by Scenario

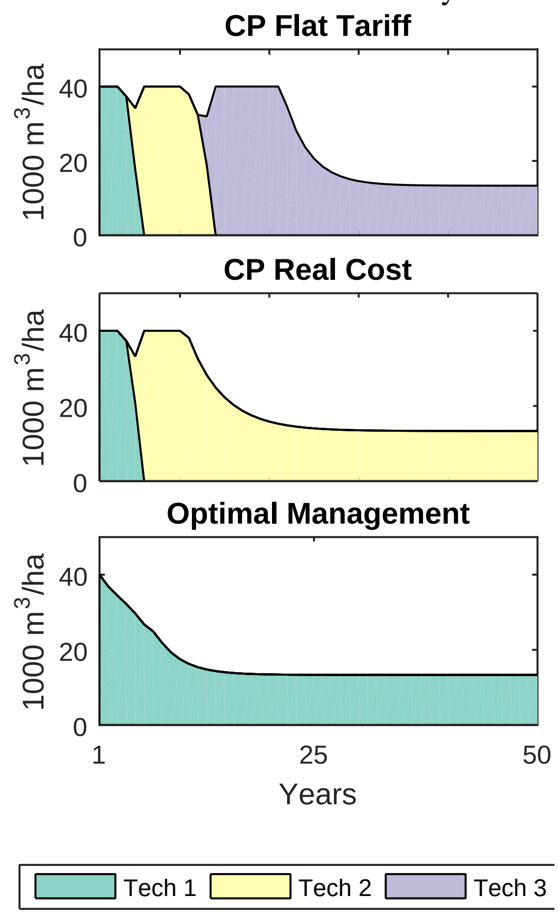


FIGURE 3. Accumulated Costs and Net Benefits

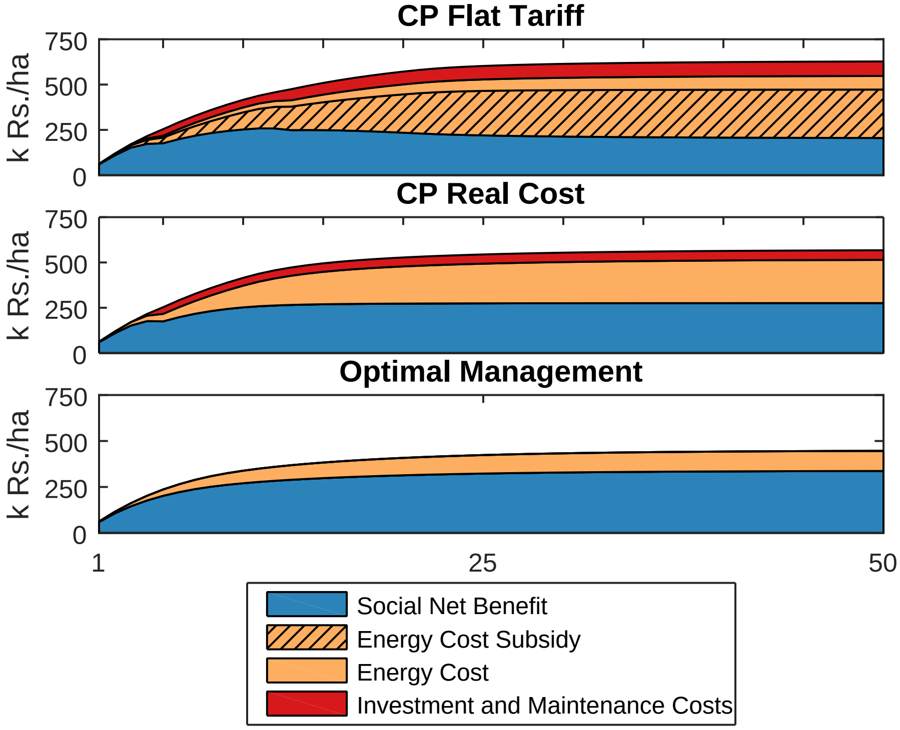
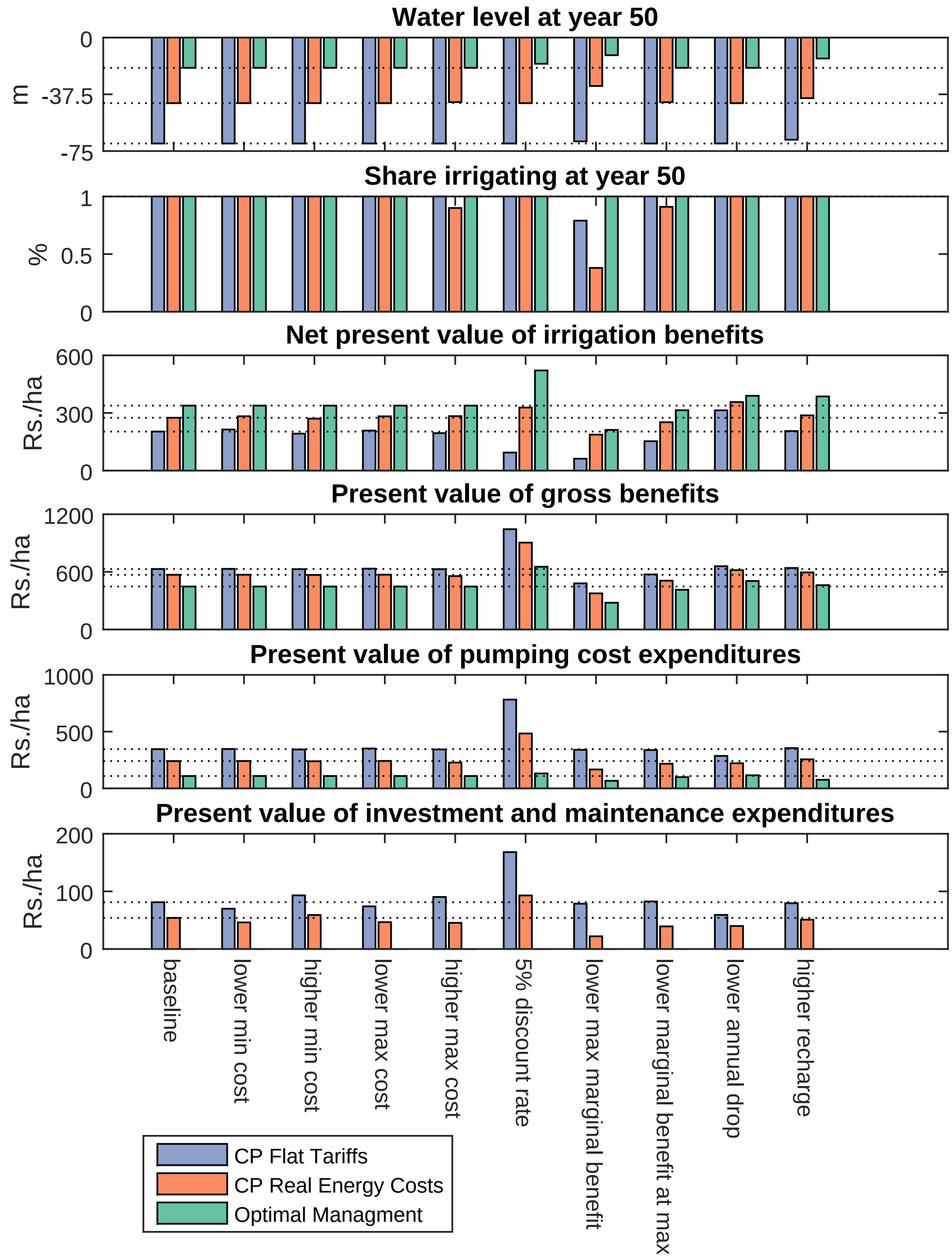


FIGURE 4. Sensitivity of Model Outcomes to Model Parameters



TABLES

TABLE I. Baseline Parameter Values

Parameter	Description	Value
r	Discount rate ($\delta = \frac{1}{1+r}$)	10%
d_0	Initial pumping lift	2m
β	Intercept of marginal benefit of water	2.00 Rs./m^3
γ	Slope of marginal benefit of water	2.18*10e-5 Rs./m^3/m^3
$\bar{w}$	Maximum water use per hectare	40,000 m^3/ha
$(\bar{d_1}, \bar{d_2}, \bar{d_3})$	Vector of maximum depths for each well type	(25, 50, 75) meters
$(\tilde{d_1}, \tilde{d_2}, \tilde{d_3})$	Vector of maximum depths at which each well type can extract $\bar{w}$	(10, 30, 60) meters
ε	Cost of energy needed to lift 1m^3 of water up 1m*	3.6*10e-2 Rs./m^3/m
(τ_1, τ_2, τ_3)	Vector of electricity tariffs for each well type**	(2.18, 6.54, 13.08) thousand Rs./ha
α	Share of applied water that percolates back to aquifer	25%
$\frac{(1-\alpha)\bar{w}}{\rho}$	Ratio of maximum consumptive use to natural inflow	3
$\frac{(1-\alpha)\bar{w}-\rho}{\phi}$	Annual drop with maximum water usage	3m
d_0	Initial pumping depth	2m
$(\chi_{11}, \chi_{22}, \chi_{33})$	Vector of baseline maintenance costs for each well type	(0,1600,4000) Rs./ha
χ_{12}	Baseline cost of moving from technology 1 to 2	39,333 Rs./ha
χ_{23}	Baseline cost of moving from technology 2 to 3	40,000 Rs./ha
χ_{13}	Baseline cost of moving from technology 1 to 3	76,000 Rs./ha
Ω	Ratio of maximum technology cost to minimum technology cost	2

$^*\varepsilon$ computed by dividing the energy needed to lift 1 cubic meter of water up 1 meter (0.0027 kWh/m^3/m) by the average pump efficiency in the region (25%) and multiplying by the true cost of energy (3.3 Rs./kWh)
$^{**}\tau_i$ computed by computing the energy needed to lift $\bar{w}$ units from $\tilde{d_i}$ and multiplying the average farm cost of electricity (0.5 Rs./kWh)

TABLE II. Sensitivity of Percentage Gains to Model Parameters

Description	Values changed from base parameters	% gain from optimal management Flat Tariffs	Real Energy Cost
Lower minimum investment cost	$\chi_{23}) = 30,000$ Rs./ha	66.0	22.6
Baseline	None	58.6	20.1
Higher minimum investment cost	$\chi_{23}) = 50,000$ Rs./ha	76.2	26.2
Lower maximum investment cost	$\Omega = 1.5$	63.7	20.4
Higher maximum investment cost	$\Omega = 2.5$	73.6	20.2
Lower discount rate	$r = 5\%$	465.9	60.0
Lower marginal benefit intercept	$\beta = 1.3$ Rs./m^3	255.6	17.9
Steeper marginal benefit slope	$\gamma = -2.88 * 10e^{-5}$ Rs./m^3/m^3	106.0	25.8
Lower annual drop	$\frac{(1-\alpha)\bar{w}-\rho}{\phi} = 2$m	24.3	9.6
Higher recharge	$\frac{(1-\alpha)\bar{w}}{\rho} = 2$	87.8	35.3