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1-1-2019

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### Recommended Citation

Sayre, Susan Stratton and Taraz, Vis, "Groundwater Depletion in India: Social Losses from Costly Well Deepening" (2019). Economics: Faculty Publications, Smith College, Northampton, MA.  
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# Groundwater depletion in India: Social losses from costly well deepening

Susan Stratton Sayre\* and Vis Taraz†

October 25, 2018

## 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 and Cline, 2003). However, this increase in groundwater use has

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We thank the editor, two anonymous referees, Katharine Sims, Esha Zaveri, and participants at the 2016 International Water Resource Economics Consortium Annual Meeting for helpful comments. An earlier version of this work was circulated under the title “Groundwater Externalities with Endogenous Well-Deepening.”

led to falling water levels and widespread concern about the long-term sustainability of irrigated agriculture (Hanjra and Qureshi, 2010).

These concerns are especially dire in India, where groundwater use has increased by 500% over the past fifty years (Garduño and Foster, 2010). The Central Groundwater Board of 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 significant concern about rapid depletion (Narula et al., 2011; Shah, 2012; Mukherji et al., 2013; Fishman et al., 2017). Evidence suggests these dropping groundwater levels have increased poverty and conflict and decreased agricultural profits (Sekhri, 2013a, 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 and 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 and Lin, 2012; Lin Lawell, 2016; Sears and Lin Lawell, 2018).

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 “myopi-

cally” 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 investments 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 and Burness (1994) who incorporate increasing demand, declining well yields, and low social discount rates, Koundouri and 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 and 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 and 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 and 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.<sup>1</sup> 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.<sup>2</sup>

Our paper also contributes to the literature on the groundwater situation in India. Msangi and Cline (2016) analyze groundwater policy options and estimate small percentage gains from groundwater management in the hard-rock aquifer region of southern India. Previous work has analyzed how subsidized, flat electricity tariffs increase groundwater extraction beyond the socially optimal level (Badiani et al., 2012; Fishman et al., 2016; Badiani and Jessoe, 2017).<sup>3</sup> Smith et al. (2015) embed these tariffs in a macroeconomic model and show that these subsidies cause spillover losses in the manufacturing sector. 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., 2017). 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 and Jessoe, 2017).

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<sup>1</sup>Recent work by Merrill and Guilfoos (2018) also addresses this question.

<sup>2</sup>While their application is to fisheries rather than groundwater, Squires and Vestergaard (2018) consider the impact of investment and knowledge spillovers in a dynamic common pool resource setting and find that the commons problem is more severe than without these features.

<sup>3</sup>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 and Lin, 2014b).

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 our numerical simulations. In Section 5, we present the results of our numerical simulations for our baseline parameters 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 conclude and discuss 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, including the states of Punjab, Haryana, parts of 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 the aquifer reaches a steady state where consumptive water extractions equal the natural inflow rate. 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 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 and Jessoe, 2017).<sup>4</sup> As water levels fall, farmers face no change in the direct cost of extracting water. 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 and Suter, 2016; Hrozencik et al., 2016; Merrill and 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 invest, farmers incur a large capital cost. Moreover, the deeper wells and larger pumps have higher 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 (Narula et al., 2011). These investments allow the farmers to maintain their previous extraction levels, circumventing the self-limiting feedback effect, at least as long as the well deepening investments remain profitable. At some point, farmers may have to migrate or exit agriculture. Fishman et al. (2017) demonstrate heterogeneity in this response, with rich farmers from socially advantaged castes being more likely to invest in deeper wells, while poorer farmers from socially disadvantaged castes are more likely to fall back on rainfed agriculture.

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

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<sup>4</sup>This monthly tariff is based on the capacity of the pump.

length of time before another round of investment will be required.<sup>5</sup> 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 incorporate limits on well capacity, endogenous investment, and flat electricity tariffs into a groundwater use model described in the next section.

### 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 potential gains from regulation. In this section, we present an analytical model describing extractions and investments under the two regimes. In Section 4, we specify functional forms and parameterize the model.

#### 3.1 Model set up

We consider a groundwater aquifer with individual farmers, indexed  $n = 1, \dots, N$ . We simplify the investment decision by granting farmers access to a series  $i = 1, \dots, I$  of technologies for extracting water. Each technology is comprised of a well of a particular depth and a corresponding pump, ordered by increasing maximum depth, and therefore also by increasing cost. We model well deepening as a discrete choice to emphasize the 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

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<sup>5</sup>Liu et al. (2014) incorporate an entry decision into a spatially explicit laboratory experiment groundwater exploitation game and observe inefficiently high entry levels.

series of fixed feasible depths.<sup>6</sup> 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 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  $s_{nt} > \tilde{s}_{nt}$  implies  $W(d_t, s_{nt}) \geq W(d_t, \tilde{s}_{nt})$ .

The instantaneous net benefit of water use as  $B(w_{nt}, d_t, s_{nt})$ , where  $w_{nt}$  is the amount of ground-water used. We assume that the gross benefits of water use are constant across technologies and depths, but that  $d_t$  and  $s_{nt}$  affect the annual net benefit by altering the energy needs and electricity charge farms face.<sup>7</sup> 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 the same technology have the benefit function.

In each period, farmers choose their next-period technology,  $a_{nt}$ . Evidence from Fishman et al. (2017) indicates significant farm-level variation in the investment decision. Investment cost varies across farms for a number of reasons including factors like wealth and caste that can influence access to credit and physical characteristics like overall farm size and degree of parcel fragmentation that can influence the effective per hectare cost of investment (Sekhri, 2011). To capture this variation, we include a farmer-specific investment cost parameter  $\omega_n$ . 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  $\omega$  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  $\omega_n$  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  $\omega_n$ .

We track  $N$  individual state variables (current well technology on each farm) and one aggregate

<sup>6</sup>See Section 5.3.1 for a discussion of how changes in the fixed depths considered influence our results.

<sup>7</sup>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.

state variable (pumping lift in the aquifer). Next period's technology on farm  $n$  is determined by this period's choice, so  $s_{nt+1} = a_{nt}$ . Since we focus 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

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

where  $\rho$  is the natural rate of inflow into the aquifer (assumed constant over time),  $\alpha$  is the percentage of water applied to crops that percolates back to the aquifer, and  $\phi$  is the volume of net water extraction that results in a one meter increase in pumping depths.<sup>8</sup>

## 3.2 Common pool regime

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 under a common pool regime

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

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<sup>8</sup>Like much of the groundwater literature, this model simplifies the true hydrology. Papers exploring the importance of spatially explicit models include Saak and Peterson (2007); Brozović et al. (2010); Guilfoos et al. (2013); Hrozencik et al. (2016); Liu et al. (2014); Manning and Suter (2016); Merrill and 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 intractable.

for farmer  $n$ 's common pool water use problem is

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

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

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

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

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

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

be the optimized value.

### 3.2.2 Investment under a common pool regime

Farmer  $n$ 's investment problem is to solve

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

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

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

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  $\mathbf{d}$ . 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

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

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

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

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).<sup>9</sup>

### 3.3 Optimal management regime

Under optimal management, the social planner's 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  $\{\mathbf{a}_1, \mathbf{a}_2, \dots\}$  and water use vectors  $\{\mathbf{w}_1, \mathbf{w}_2, \dots\}$  where  $\mathbf{a}_t$  is an  $N \times 1$  vector of technology choices with  $a_{nt} \in \{1, \dots, I\}$  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 both discrete and

<sup>9</sup>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.

continuous choices, giving the nested optimization problem:

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

subject to

$$0 \leq w_n \leq W(d, s_n) \quad (11)$$

for all  $n$ .

The first order conditions for annual water use and investment choices under optimal management are derived in the following section and compared to those from the common pool regime.

### 3.4 Comparison of the common pool and optimal management regimes

The differences between the optimal management and common pool scenarios are described in the following four propositions.

**Proposition 1.** *Farms will pump more water in the common pool scenario than is optimal.*

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

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

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

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

$$W(d, s_n) - w_n \geq 0 \quad (15)$$

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 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, overpumping will be exacerbated by overinvestment.

**Proposition 2.** *Farmers will more invest in the common pool scenario than is optimal.*

As in the common pool scenario, we 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

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

for all  $j \neq i$ . 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 two differences between the two investment regimes. The first line gives the discounted continuation value of having better technology next period and is analogous to the right hand side of Eq. (8). The second two lines represent the impact of changes in water use in response to the investment. If the social plan-

ner elects to invest, the vector of water use this period will change as well. Since  $\tilde{\mathbf{w}}_t$  maximizes  $\sum_{n=1}^N (B(w_n, d, s_n)) + \delta V(g(\mathbf{w}, d), \tilde{\mathbf{a}})$ , we know that the magnitude of the last line is greater than the magnitude of the second line, implying that the benefit of investment will be lower under optimal management than under common pool. The social planner will be more likely to maintain the current technology. Intuitively, investment implies more pumping today, which lowers future water levels and lowers the continuation value.

**Proposition 3.** *Overinvestment in well capacity will exacerbate common pool overpumping.*

The water use conditions (Eqs. 3 and 12) both contain a Lagrange multiplier for the well capacity constraint. Since farmers are more likely to invest in deeper wells under the common pool scenario, this constraint is less likely to bind at a given depth. As a result, overpumping in the common pool scenario will increase further.

**Proposition 4.** *Overpumping will exacerbate common pool overinvestment, due to rational expectations.*

Similarly, the investment conditions (Eqs. 8 and 16) both contain a term that measures the increase in continuation value attributable to better technology. 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.

Neither of our problems have closed-form solutions, so we turn to numerical simulation. Given the high dimensionality of the optimal management problem, we first modify the problem to focus on the share of farms using each technology. This modification is described in the Online Appendix. 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

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 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  $\varepsilon$  equal to the estimated true cost of the electricity needed to lift one cubic meter of water one meter and set  $\tau$  to zero. In the common pool simulations that reflect the flat tariffs in our study region, we set  $\varepsilon = 0$  and have non-zero values of  $\tau$ .

Investment in this region primarily comes in the form of deepening existing wells and purchasing new and more powerful pumps. We adopt a simple formula for the extraction capacity given a farmer's current technology and the water depth. Each technology 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 giving a water

limit function of

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

Our investment cost has two components. First, we identify a baseline level of maintenance expenditures for each technology (denoted by  $\chi_{ii}$ ) and a baseline cost of moving from technology  $i$  to technology  $j$  (denoted by  $\chi_{ij}$ ). 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  $\omega$  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  $\Omega$ .

## 4.2 Parameterization

We now describe how we selected our parameter values. Table I presents the parameter values; additional details about their derivation are given in the Online Appendix.

### 4.2.1 Water benefit parameters

We assume the average farmer has four hectares of land that they plant for three cropping seasons: one rainy season and two dry seasons.<sup>10</sup> The primary crops are rice, pulses and oilseeds. Rice is water-intensive and must be irrigated but can be cultivated in all three seasons. Pulses and oilseeds do not require irrigation but are only grown during the rainy season. We construct a water benefit function reflecting farmers' options about which of these crops to grow: specifically what acreage

<sup>10</sup>The rainy season is *kharif* (June–September) and the dry seasons are *rabi* (November–February) and the summer season (March–May).

of rice to grow (and irrigate) each season.<sup>11</sup> We use the rice irrigation requirements from Fishman et al. (2015) and net revenue estimates from ICRISAT (2015) to calculate the maximum value of water potentially used and the marginal benefit of water.<sup>12</sup> We find a farm may use up to 40,000 m<sup>3</sup> of water per hectare (ha) of land. We estimate that the marginal benefit of water ranges from 1.3 Rs./m<sup>3</sup> of water during the rainy seasons to 1.13 Rs./m<sup>3</sup> during the dry seasons, suggesting a very flat marginal benefit of water curve (see the Online Appendix for more details). 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<sup>3</sup> for the first unit of irrigation water to 1.13 Rs./m<sup>3</sup> at the maximal level of extraction (40,000 m<sup>3</sup>/ha). Beyond this level, we set the marginal benefit of water to zero. We discount benefits and costs at 10% per year.

#### 4.2.2 Well technology and cost parameters

Each well technology choice includes the depth of the well and the horsepower of the associated pump. Groundwater pumps must provide appropriate power for the depth of the well.<sup>13</sup> For tractability, we selected three well types, with maximum depths of extraction that are representative of tubewells in our region—25, 50, and 75 meters—each matched with an appropriately sized pump (Ministry of Water Resources, 2007).<sup>14</sup> 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.

To estimate the cost of moving between our three well technologies, we use cost estimates for tubewells and electric pumps from Ministry of Water Resources (2007) and Sekhri (2011). We

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<sup>11</sup>We model the problem this way because 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., 2017).

<sup>12</sup>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.

<sup>13</sup>A pump that is too powerful will waste electricity and draw sediment and 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).

<sup>14</sup>In Section 5.3.1, we test the robustness of our results considering simulations with different well technology choices.

include cross-farmer variation in investment costs to capture variation in characteristics such as wealth, caste, information, credit, and land characteristics. Parameter values are listed in Table I and the Online Appendix provides additional details on their construction. We use data on annual maintenance costs from Ministry of Water Resources (2007) to set the annual annual maintenance costs of each technology. Since investment costs are important in our model, we conduct several comparative static simulations varying different elements of the cost function, to address the difficulty of precisely estimating these cost parameters.

We use estimates of pump-specific flat rate electricity tariffs from Badiani and Jessoe (2017) to estimate the cost of electricity and our electricity tariff parameters for each well type.

### **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 and we use a value of 25% for this parameter, based on data from 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. Specifically, we set it equal to one-third of maximum consumptive use, based on groundwater usage estimates from (Suhag, 2016) and sown area estimates from Fishman et al. (2016) (see the Online Appendix for more details). To parameterize aquifer storativity, we use an inductive approach. Groundwater levels have been dropping as much as 3 m per year with current extraction (Fishman et al., 2017). We infer a storativity value by assuming that if all farmers in the region fully irrigated their land every year, water levels would drop 3 m each year.

## 5 Results

### 5.1 Baseline simulations

The water level and associated pumping cost in each of our three scenarios with our baseline parameters are illustrated in Figure 1, while Figure 2 illustrates water use in the region over time. Given the parameters described in the previous section, the sustainable steady-state level of water use in all three scenarios is  $13,333 \text{ m}^3/\text{ha}$  (of which  $10,000 \text{ m}^3/\text{ha}$  is consumptive). The height of the top line in each panel of Figure 2 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  $40,000 \text{ m}^3/\text{ha}$ , water use never exceeds this level. Finally, Figure 3 presents the cumulative present value of costs and net benefits for the first 50 years in each case.

**Result 1.** *Optimal management increases net social benefit by 66% relative to a common pool regime with flat tariffs.*

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. The water level drops rapidly until the volume of water that can be pumped from type 1 wells begins to decline. Farms then rapidly invest in deeper wells to restore their ability to fully irrigate their land. The decline resumes and the same pattern repeats when type 2 wells begin to fail.<sup>15</sup> Since our model includes only three technologies, 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 recharge level. As we demonstrate in Section 5.3.1, when we include the option to investment in another technology, we see continued investment.

With flat tariffs, water levels stabilize at 70m below the surface. At this level, the actual cost of pumping water to the surface exceeds the marginal benefit of water. This is consistent with

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<sup>15</sup>Note that although farmers in our model have the option to invest in type 3 wells immediately, saving roughly 4% of the total investment cost by making a single transition. Given the discount rate, farms save more by delaying the second investment.

studies suggesting that if farmers were paying the full cost of their electricity use, profits would be negative (Narula et al., 2011). Irrigation imposes a social cost of almost 15,000 Rs./ha each year. However, under flat tariffs, farmers with type 3 wells pay a low tariff and earn profits in the steady-state.

The optimal management scenario is starkly different. Since water extractions in the steady-state are limited to 13,333 m<sup>3</sup>/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. The investment increases the cost of farming twice: water costs more to extract, and the investment cost itself is wasteful. Optimal management sharply curtails pumping on individual farms. Water levels are allowed to drop to 20m since type 1 wells can extract the sustainable level from this depth. Farms have the same marginal value of water as they do in the flat tariff case, but extraction costs are much lower. Instead of losing roughly 15,000 Rs./ha each year in the steady-state, society gains approximately 15,000 Rs./ha annually.

Given this stark contrast, 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. Still, since they are only 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.<sup>16</sup>

**Result 2.** *Marginal cost electricity pricing reduces but does not eliminate the gain from optimal management.*

Farmers in our second set of baseline simulations face the actual marginal cost of electricity but no regulatory limitations on water usage. As under flat tariffs, water levels drop rapidly and,

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<sup>16</sup>Note that this does not suggest that the common pool outcome maximizes the benefits to farmers under flat tariffs. Finding 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.

as type 1 wells 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. While the marginal benefit of water exceeds the marginal cost by a small amount, farms are limited by the extraction capacity of their wells. They elect not to invest in type 3 wells because the small gain is not large enough to justify the cost.

Because farmers avoid the second wave of well deepening, the social benefit increases roughly 35% relative to flat tariffs. 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. But, the common pool problem remains critical; even when farmers are charged the true cost of electricity, implementing optimal management will increase the aggregate benefit of irrigation by nearly 23%. Moreover, this percentage may understate 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. Waiting to implement regulation until type 1 wells begin to fail lowers the overall social benefits, but 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.<sup>17</sup>

The Online Appendix contains detailed descriptions of these simulations; we summarize the major

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<sup>17</sup>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.

findings here.

**Result 3.** *The percentage gains from management first rise with increases in investment cost and then fall due to exit from agriculture.*

We conduct a series of simulations varying the support of the investment cost distribution, including a mean-preserving contraction and raising or lowering each bound independently. We find a non-monotonic effect of increasing investment cost on the percentage gains from management. Since it makes socially wasteful investment more expensive, including higher 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 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.

**Result 4.** *Low social discount rates lead to large gains from optimal management.*

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 significantly influences the estimated results, as Brill and Burness (1994) demonstrate and our results confirm.

**Result 5.** *Lowering the choke price of water increases exit from irrigated agriculture. It increases the percentage gain from optimal management relative to flat tariffs and decreases the percentage gain relative to real marginal cost pricing.*

Reducing the choke price of water 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 in the common pool scenarios.

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%.

**Result 6.** *Increasing aquifer storativity lowers the benefit of optimal management.*

As expected from the Gisser-Sanchez literature, high aquifer storativity tends to make the gains from management smaller (see e.g. Koundouri (2004)). Reducing the rate of aquifer decline by one-third reduces our estimated gains 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.

## 5.3 Model variations

We also test the sensitivity of our results to two model variations. First, we consider a more flexible set of well technologies. Second, we model farmers as having adaptive expectations over future groundwater depths, instead of rational expectations as in our baseline scenario.

### 5.3.1 Variations in the set of available well technologies

Our baseline simulations include three well technologies because the optimal management problem proved numerically intractable with more than three dimensions. However, it is important to verify that the constraint of three well types is not driving our results. In addressing this point, we explore

the optimal management regime and the common pool regime separately.

For the optimal management regime, recall that the social planner only uses the first of the three available technologies. Introducing additional technologies could never *lower* the net present value that we compute with this set of three technologies, because the social planner would always have the option not to choose the additional technologies. Therefore our estimate is a lower bound on the net present value under optimal management. On the other hand, it is possible we could be underestimating the net present value under optimal management. To explore this, we maintain three technologies but reduce the depths of the latter two options. 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.

For the common pool problem, we note that the curse of dimensionality is substantially milder than it is for our optimal management problem. Our common pool model can be solved in a reasonable time frame as long as we keep the number of available technologies under 10. 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.

For the flat tariff common pool scenario, we first consider 10m increments instead of our baseline 25m increments and maintain a maximum depth of 75m. This change slightly increases the gains from imposing optimal management to 67.5%. We then maintain the 10m increments but add more choices until the maximum depth is 115m. When offered the option, most farmers elect to continue deepening their wells 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. 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 used 5m increments and a maximum depth of 55m. 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 lowers 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 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 investment patterns like those described in Perveen et al. (2012) better than continual small adjustments. 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 consider multiple technologies and vary the shares of the investment costs that are fixed and the portion that depend on the depth of the final well, irrespective of starting point. 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. 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.

### **5.3.2 Adaptive expectations about water levels**

Our baseline simulations assume farmers have rational expectations about future groundwater levels. We conduct additional simulations where 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 adaptive expectations make the common pool scenario somewhat 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. Slower investment increases the social benefits of the common pool scenarios. As a result, the gain from imposing optimal management falls to 55% relative to flat tariffs and 19% relative to real marginal cost pricing. Although the estimates are smaller, they suggest that our finding of large gains is robust to scenarios under which farmers have either rational or adaptive expectations about future groundwater levels.

## 6 Discussion

Our 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 (Zaveri et al., 2016; Fishman, 2016; Taraz, 2017; Fishman, 2018). 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.<sup>18</sup>

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.<sup>19</sup>

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, 2013b; Fishman et al., 2016). Including the option to invest in efficient irrigation technology is beyond the scope of our model. We also note that efficient irrigation has a much smaller impact on consumptive use of water than it does on applied water. Moreover, evidence suggests that improved irrigation technology may expand irrigated acreage and ultimately increase

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<sup>18</sup>In the Online Appendix, we explore the use of electricity prices greater than marginal cost to reduce the common pool externality.

<sup>19</sup>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.

water consumption (Pfeiffer and Lin, 2012, 2014a; Fishman et al., 2015).

## 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 common pool groundwater use with flat electricity tariffs and 23% relative to a common pool scenario where farmers pay the full marginal costs of electricity. These estimates are much higher than many existing studies of groundwater management gains.

Previous work has documented the impact of electricity subsidies on increased pumping, but we make a critical contribution to this 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 compound the others. For instance, while Badiani and 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 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 reveal 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., 2017).

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 and 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

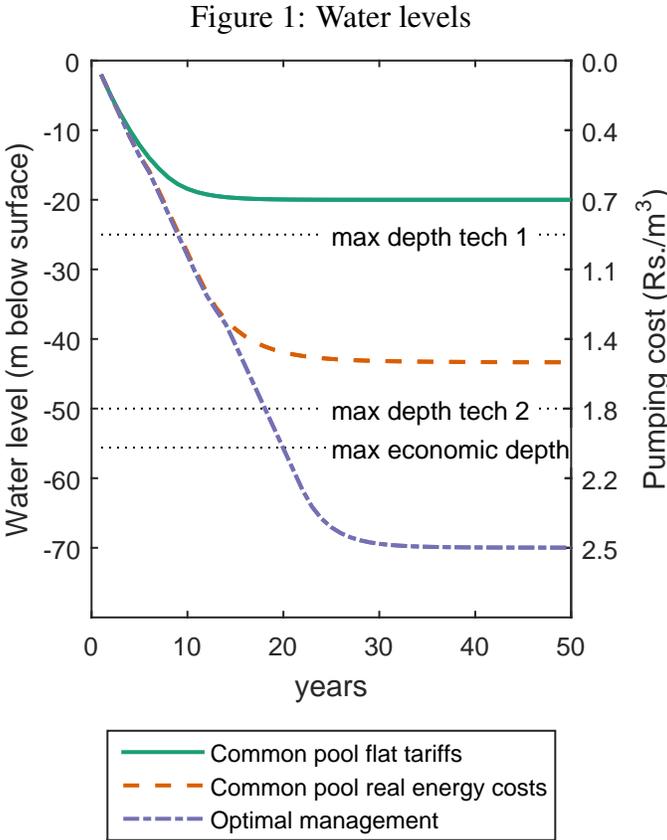
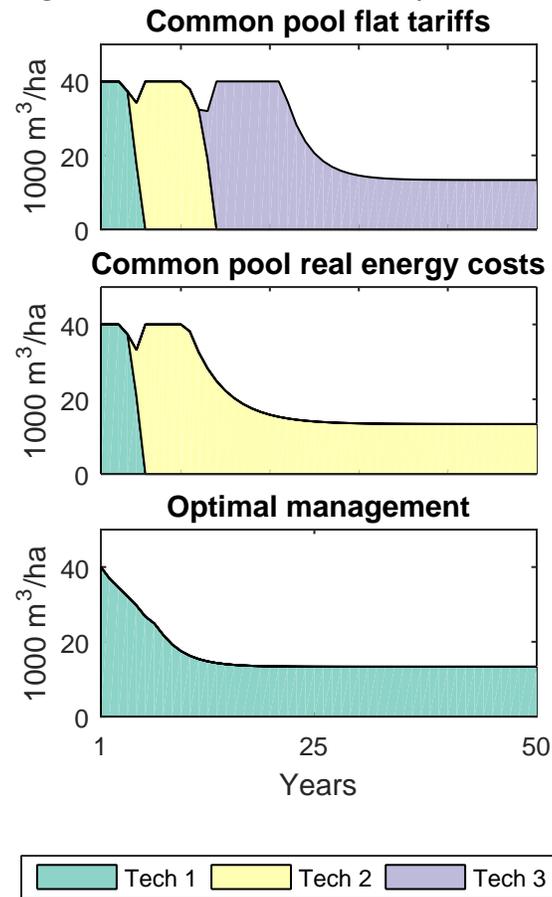


Figure 2: Water use over time by scenario



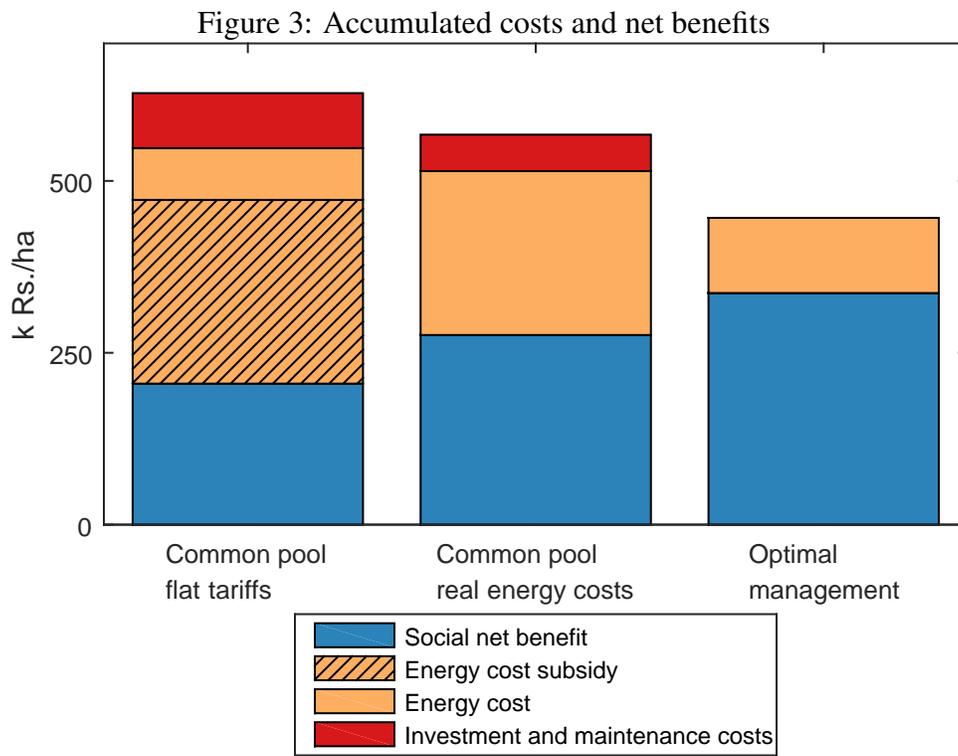
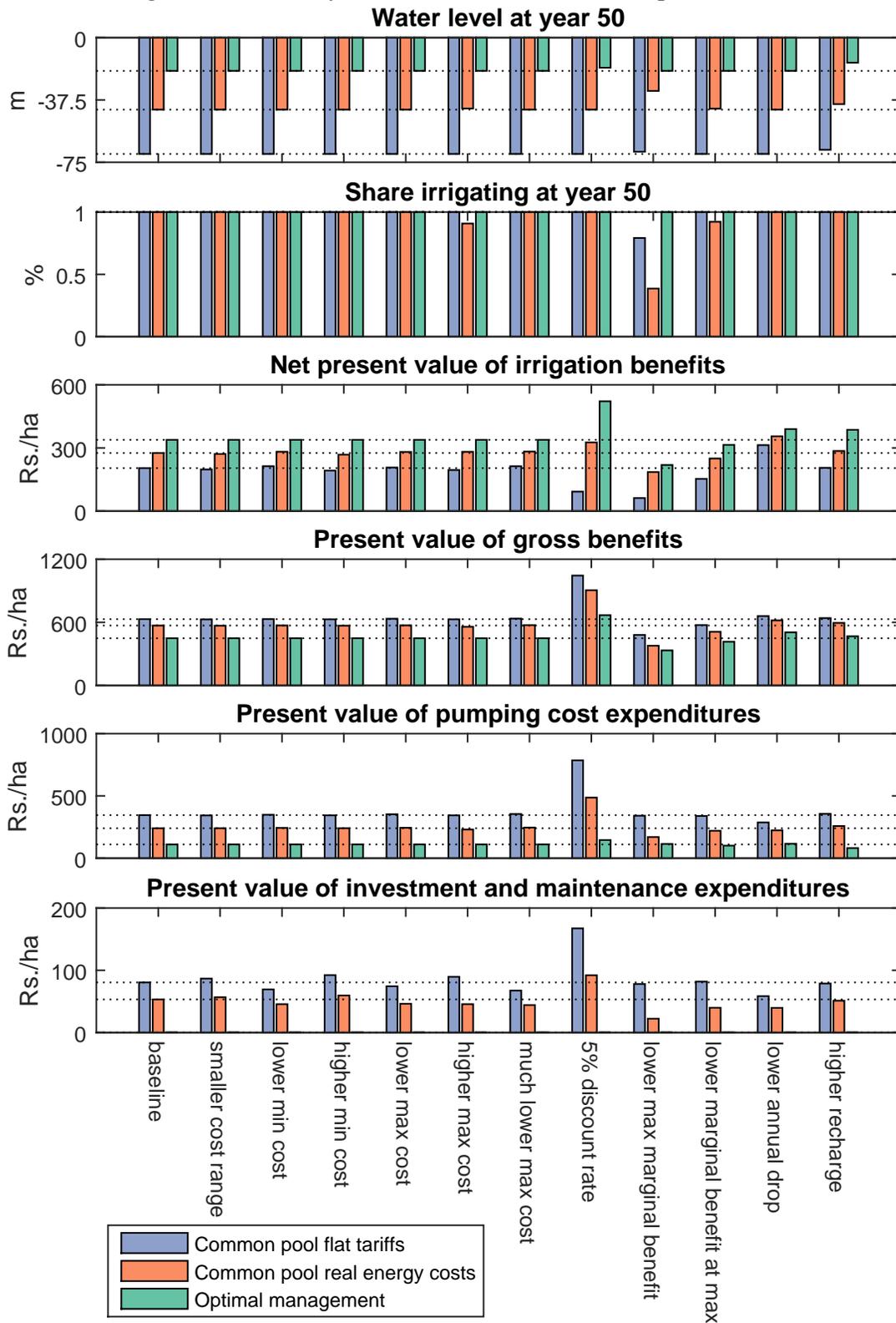


Figure 4: Sensitivity of model outcomes to model parameters



## Tables

Table I: Baseline Parameter Values

Parameter	Description	Value
$r$	Discount rate ( $\delta = \frac{1}{1+r}$ )	10%
$d_0$	Initial pumping lift	2m
$\beta$	Intercept of marginal benefit of water	2.00 Rs./m <sup>3</sup>
$\gamma$	Slope of marginal benefit of water	2.18*10e-5 Rs./m <sup>3</sup> /m <sup>3</sup>
$\bar{w}$	Maximum water use per hectare	40,000 m <sup>3</sup> /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
$\varepsilon$	Cost of energy needed to lift 1m <sup>3</sup> of water up 1m*	3.6*10e-2 Rs./m <sup>3</sup> /m
$(\tau_1, \tau_2, \tau_3)$	Vector of electricity tariffs for each well type**	(2.18, 6.54, 13.08) thousand Rs./ha
$\alpha$	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
$\chi_{12}$	Baseline cost of moving from technology 1 to 2	39,333 Rs./ha
$\chi_{23}$	Baseline cost of moving from technology 2 to 3	40,000 Rs./ha
$\chi_{13}$	Baseline cost of moving from technology 1 to 3	76,000 Rs./ha
$\Omega$	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<sup>3</sup>/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
Baseline	None	66.0	22.6
Smaller investment cost range	$(\chi_{23} = 55,000 \text{ Rs./ha}, \Omega = 1.18)$	71.1	24.8
Lower minimum investment cost	$\chi_{23} = 30,000 \text{ Rs./ha}$	58.6	20.1
Higher minimum investment cost	$\chi_{23} = 50,000 \text{ Rs./ha}$	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
Much lower maximum investment cost	$\Omega = 1.125$	58.8	19.7
Lower discount rate	$r = 5\%$	465.9	60.0
Lower marginal benefit intercept	$\beta = 1.3 \text{ Rs./m}^3$	255.6	17.9
Steeper marginal benefit slope	$\gamma = -2.88 * 10e^{-5} \text{ Rs./m}^3/\text{m}^3$	106.0	25.8
Lower annual drop	$\frac{(1-\alpha)\bar{w}-\rho}{\phi} = 2\text{m}$	24.3	9.6
Higher recharge	$\frac{(1-\alpha)\bar{w}}{\rho} = 2$	87.8	35.3

## Online appendices: Not intended for print publication

### A A numerically feasible optimal management problem

The optimal management problem described in the text 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  $\mathbf{w} = (w_1, \dots, w_I)$ . For notational compactness, we also define a vector version of the instantaneous net benefit function  $\mathbf{B}(\mathbf{w}, d) = (B(w_1, d, 1), \dots, B(w_I, d, I))$  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  $\mathbf{z} = (z_1, \dots, z_I)$  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. The total cost of next period's technology choices is  $K(\mathbf{X}, \mathbf{z})$ .

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. This results in an optimal management problem given by

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

subject to

$$\begin{aligned}
 d_{t+1} &= d_t + \frac{(1-\alpha)N\mathbf{z}'\mathbf{w} - \rho}{\phi} \text{ for } t = 0, \dots, \infty \\
 \mathbf{z}_{t+1} &= \mathbf{X}_t \mathbf{z}_t \text{ for } t = 0, \dots, \infty \\
 \sum_{i=1}^I x_{ijt} &= 1 \text{ for } t = 0, \dots, \infty \text{ and } j = 1, \dots, I \\
 0 \leq w_{it} &\leq W(d_t, i) \text{ for } t = 0, \dots, \infty \text{ and } i = 1, \dots, I
 \end{aligned}$$

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

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

subject to

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

and

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

As described in the model section, our parameterization uses the farm specific cost function

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

with  $\omega$  distributed uniformly between 1 and an upper bound  $\Omega$ . 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  $\omega$  values associated with each technology from the shares using each technology. The investment cost function under optimal management is 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  $\mathbf{X}$ . To derive these bounds we note that all farms with  $\underline{\omega}_i(\mathbf{z}) < \omega_n \leq \bar{\omega}_i(\mathbf{z})$  are currently using technology  $i$ . The cutoff values are given by  $\bar{\omega}_i(\mathbf{z}) = F(\sum_{j < i} z_j)$  and  $\underline{\omega}_i(\mathbf{z}) = F(\sum_{j \leq i} z_j)$ . 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  $\omega_{ij}^{UB}(\mathbf{X}, \mathbf{z}) =$

$$F(\bar{\omega}_j(\mathbf{z}) - z_j \sum_{k < i} x_{kj}) \text{ and } \omega_{ij}^{LB}(\mathbf{X}, \mathbf{z}) = F(\bar{\omega}_j(\mathbf{z}) - z_j \sum_{k \leq i} x_{kj}).$$

## B Parameterization appendix

In this appendix, we give additional details on how we selected our parameter values.

### B.1 Benefit of water

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., 2015). 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<sup>3</sup> 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., 2017).

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). 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. 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<sup>3</sup> of water during kharif and 1.13 Rs./m<sup>3</sup> during summer and rabi, suggesting a very flat marginal benefit of water curve.

### B.2 Well technologies and costs

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).

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

### **B.3 Aquifer parameters**

We use a value of 25% for the return flow coefficient, 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<sup>3</sup> applied to a fully irrigated ha returns to the aquifer, maximum consumptive use is 30,000 m<sup>3</sup>/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<sup>3</sup>/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., 2017). 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.

## **C Comparative statics appendix**

### **C.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 five variations: (a) a mean-preserving contraction of the distribution ranging from 55,000 Rs./ha to 65,000 Rs./ha, (b) lowering the minimum investment cost from 40,000 Rs./ha to 30,000 Rs./ha, (c) raising the minimum investment cost to 50,000 Rs./ha, (d) lowering the maximum investment cost from 80,000 Rs./ha to 60,000 Rs./ha, (e) raising the maximum investment cost to 100,000 Rs./ha, and (f) lowering the maximum investment cost to 45,000 Rs./ha. 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.

Most of these 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.

Raising the maximum investment cost to 100,000 Rs./ha, has a similar impact as the other cases 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%.

## **C.2 Lower discount rate**

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.

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.

## **C.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<sup>3</sup>/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. This simulation is described in the text.

One real world change that could lead to this shift would be the introduction of higher value dryland crops and/or increases in the price of such crops. 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.<sup>20</sup> 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 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 to 106%. 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%.

#### **C.4 Changes in 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

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<sup>20</sup>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.

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.

## **C.5 Changes in the price of electricity**

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. 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.

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.

## **D Model variations appendix**

### **D.1 Detailed descriptions of simulations varying well technologies**

As described in the text, we address optimal management and common pool scenarios separately.

#### **D.1.1 Variations under optimal management**

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. 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. These results suggest that limiting the options available to the social planner did not materially change the character of the optimal management solution.

#### **D.1.2 Variations under common pool regimes**

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 Rs./ha, increasing the gains from imposing optimal management to 67.5%.

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.

We then 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. Additional simulations with larger well increments and deeper maximum depths confirm this fact. 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%.

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. Some farms elect to exit agriculture instead of deepening their wells in this wave. 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%.