Groundwater Management under Heterogeneous Land Tenure Arrangements [*]

Sanval Nasim Steven Helfand Ariel Dinar

Abstract

We develop a groundwater extraction model that considers the Marshallian inefficiency associated with sharecropping and use data from Pakistan to simulate the impact of an open access regime and of optimal management on groundwater extractions, the state of the aquifer, and annual net benefits through time. We also evaluate a price instrument as a mechanism of inducing optimal extractions. Under both open access and optimal management, we observe notable differences in groundwater extractions and the water table level between the tenure model (which considers the behavior of both owner cultivators and sharecroppers) and the baseline model (which includes the behavior of only owner cultivators). We also find a modest difference in the aggregate net benefits generated by the two models. The results offer new insights—vis-à-vis land tenure heterogeneity—into the evaluation of more effective policies for groundwater management and aquifer sustainability.

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[*] Nasim (corresponding author): Assistant Professor, Department of Economics, Lahore University of Management Sciences, Khayaban-e-Jinnah, Phase 5 DHA, Lahore, Pakistan, +92 42 35608461, sanval.nasim@lums.edu.pk. Helfand: Associate Professor, Department of Economics, University of California, Riverside, 900 University Avenue, Riverside, CA 92521, USA, +1 951 827 1572, steven.helfand@ucr.edu. Dinar: Distinguished Professor, School of Public Policy, University of California, Riverside, 900 University Avenue, Riverside, CA 92521, USA, +1 951 827 4526, ariel.dinar@ucr.edu. We would like to acknowledge the International Food Policy Research Institute (IFPRI) for funding this study through the Pakistan Strategy Support Program. IFPRI has circulated an earlier version of this manuscript as a working paper under the title "Optimal Groundwater Management in Pakistan's Indus Water Basin" (IFPRI PSSP Working Paper 34). At UCR, we would like to thank Ken Baerenklau for his insightful comments and Keith Knapp for his assistance with the programming involved in the research. We would also like to acknowledge participants at the annual conferences of the Association of Environmental and Resource Economists and the European Association of Environmental and Resource Economists for their constructive suggestions.

1 Introduction

Does sharecropping improve groundwater stock and net returns to irrigated agriculture over time? Do groundwater stock and net returns in the presence of sharecropping significantly differ across groundwater management schemes such as open access and optimal management? How does the revenue from a charge on groundwater extractions vary across sharecroppers and owner cultivators? We evaluate these questions by introducing land tenure heterogeneity in a dynamic groundwater model; calibrating the model using economic and hydrological data from an aquifer in a developing country; and simulating the outcomes over a long-term horizon.

Groundwater depletion and its sustainable management have garnered considerable attention in the literature. Evidence suggests that a lack of effective groundwater governance has led to the overdraft of aquifers and the deterioration of its quality in several regions, including the US, Mexico, Spain, India, and Pakistan (Shah 2014, 2007). The overdraft of aquifers and its impact on irrigation costs is particularly alarming given the increasing reliance of developed and developing countries in arid and semi-arid zones on groundwater. Farmers in countries such as Pakistan and India, which have large agrarian sectors, extract groundwater to meet at least half of their irrigation water demand.

Since Gisser and Sanchez (1980) presented the paradoxical result that the social benefits of optimal management of groundwater are insignificant compared to the returns under an open access regime—known as the Gisser-Sanchez effect—several researchers have focused on verifying their conclusions under different economic and hydrological assumptions (Feinerman and Knapp 1983; Lee, Short, and Heady 1981; Nieswiadomy 1985; Allen and Gisser 1984). Some have compared the two management regimes by including water quality as an additional control (Knapp and Baerenklau 2006; Roseta-Palma 2002). Others have developed models that take into account the spatial nature of the pumping externality, the incentives of a backstop technology, and the impact of groundwater-dependent ecosystems (Merrill and Guilfoos 2018; Brozović, Sunding, and Zilberman 2010; Koundouri and Christou 2006; Esteban and Dinar 2016).

A subset of studies have evaluated groundwater management in the context of stochastic rainfall and surface water supplies (Merrill and Guilfoos 2018; Knapp and Olson 1995; Tsur and Graham-Tomasi 1991; Tsur 1990). Worthington, Burt, and Brustkern (1985) have examined the impact of heterogeneity in land productivity on the benefits of optimal management, finding that the difference in the social benefits between the two management regimes substantially increases with greater heterogeneity in productivity.

The economic literature on dynamic resource management is extensive but the effects of land tenure heterogeneity—land that is owner cultivated or is under tenancy contracts such as sharecropping—on the dynamics of resource extraction have yet to be investigated. Sharecropping, which has received wide attention in the literature for decades, is a common form of tenancy in South Asia, South East Asia, and Sub-Saharan Africa, and to an extent, in some parts of Europe and the US (Gebrehiwot and Holden 2019; Bidisha et al. 2018; Sadoulet, de Janvry, and Fukui 1997; Shaban 1987; Nabi 1986).

The tenancy literature (Stiglitz 1974; Braverman and Stiglitz 1986; Agrawal 2002; Quibria and Rashid 1984; Hayami and Otsuka 1993) has demonstrated the existence of Marshallian inefficiency in sharecropping—the idea that output sharing between a tenant and a landlord acts as a (ad valorem) tax on the tenant's effort, inducing the tenant to reduce output and input below their competitive levels. Most models in the sharecropping literature have exclusively included the effect of Marshallian inefficiency on labor effort. However, the perverse effects of sharecropping through Marshallian inefficiency can be observed in the application of production inputs besides labor (Jacoby and Mansuri 2008).

Empirical evidence reveals that sharecroppers exhibit lower irrigation intensity compared to owner cultivators as a result of Marshallian inefficiency (Arcand, Ai, and Éthier 2007; Shaban 1987). Jacoby, Murgai, and Ur Rehman (2004) have argued that labor effort and contractible inputs such as groundwater are complements in agricultural production. Therefore, as labor effort falls owing to Marshallian inefficiency, so might groundwater use.

A separate strand of literature has established a strong link between sharecropping and groundwater markets. Prakash (2005) has shown that sharecropping contracts with unfavorable terms for tenants increase in areas with declining groundwater markets. Moreover, sharecroppers are often unable to procure groundwater at competitive prices owing to monopolistic markets (Jacoby, Murgai, and Ur Rehman 2004; Sugden 2015).

The literature shows that sharecroppers face differential contractual and market conditions relative to other tenants, which affects their decisions regarding groundwater extractions and purchases at the margin. This carries important implications for groundwater management and sustainability in agricultural regions with heterogeneous land tenure arrangements. For example, Marshallian inefficiency would influence the long-term stock of groundwater in aquifers shared by owner cultivators and sharecroppers through its effect on extractions.

In this paper, we investigate the implications of sharecropping—vis-à-vis Marshallian inefficiency—for groundwater management over a long time-horizon through a resource extraction model. We calibrate the model with data from Pakistan's Sindh province, where a third of irrigated agricultural land is under sharecropping. We simulate the effect of an open access regime (the status quo) and of optimal management on groundwater extractions, the water table level, and annual net benefits from irrigated agriculture. We also derive a price instrument that induces the optimal levels of extractions in each time period.

Under both open access and optimal management, we find significant differences between the states of the aquifer given by our model that includes sharecroppers and owner cultivators and the counterfactual model that includes only owner cultivators. The Marshallian inefficiency induces sharecroppers to extract less groundwater than owner cultivators leading to a divergence in the water table levels given by the two models through time. At steady state, the difference in the water table levels is 6.4 meters under open access and 9.7 meters under optimal management—this translates into a difference in the steady state annual net benefits of 2.6 percent (open access) and 3.1 percent (optimal management).

Our results demonstrate that though sharecropping reduces agricultural production, it can inadvertently improve the stock of groundwater, and hence net returns to irrigated agriculture, overtime. Our results offer a benchmark for policymakers to evaluate the impact of groundwater management on social efficiency across owner cultivators and sharecroppers in our study area. They also create tension for policymakers interested in the welfare impact of increasing landownership in regions with a sizable proportion of sharecroppers.

The sharecropping literature further shows that owner cultivators and fixed-rent tenants have similar production decisions in many observed cases. Thus, we exclude fixed-rent tenancy from the analysis. While a vast body of work explores other dimensions of sharecropping such as risk-sharing, liquidity constraints, and tenure security (threat of eviction), this study is the first to focus solely on Marshallian inefficiency in the context of dynamic resource use on sharecropped lands.

Evidence suggests that groundwater salinity affects the extraction decisions of farmers in our study area. However, the salinity dimension is not a first-order concern of our analysis as it decreases the tractability of the results. Thus, we exclude groundwater salinity from the analysis.

The next section presents a model of groundwater extractions. Section 3 describes the data and the model calibration. Section 4 presents the results of the model while Section 5 analyzes an optimal extraction price policy. The final section concludes.

2 Model

In this section, we first present our hydrological-economic model, accounting for differences in land tenure. We then explain the decision rules for deriving solutions under open access and under optimal management. We acknowledge that the model developed below is not an operational model of our setting (Sindh) since it's not calibrated to explain the spatial variation in aquifer characteristics. In many parts of Sindh, excessive surface water seepage can lead to waterlogging, which might remain unaffected by groundwater extractions in other parts of the province. Our model captures general effects of groundwater extractions and emphasizes long-run dynamics, permitting us to isolate the impact of land tenure heterogeneity on the broader state of the aquifer.

2.1 Groundwater Extraction Problem

We depart from the traditional groundwater management literature to formulate a hydrological-economic model that accounts for the impact of tenure on groundwater extractions. The dynamic model that we develop links hydrological and economic variables of groundwater usage. We acknowledge that changes in land use, cropped area, and cropping intensity are important in determining net benefits over time, but since our focus is solely on the impact of land tenure on the aquifer state, we use simplified, yet reasonable assumptions to keep the model tractable.

We assume a linear reduced-form aggregate water demand function for the entire irrigated crop area. The inverse water demand function is given by $p(q_t) = a_0 - a_1(q_t)$, where $p(q_t)$ is the marginal willingness to pay for irrigation water (surface water and groundwater) in rupees per cubic meter ($\mathrm{Rs\,m^{-3}}$) in time period t; q_t is the quantity of irrigation water (a homogenous input) in billion cubic meters ($\mathrm{Bm^3}$); a_0 is the intercept of the water demand function; a_1 is the slope of the water demand function; and t is a time subscript.

The quantity of irrigation water is $q_t = (1-\beta_{sw})q_{sw} + q_{gw_t}$, where q_{sw} is a parameter representing the total quantity of surface water available in the canal commands for irrigation;[1] β_{sw} is the percentage of surface water that seeps into the aquifer during delivery from the canal level to the field level; $(1-\beta_{sw})$ is the surface water delivery efficiency and shows the percentage of surface water available at the field level after passing through the canal system; and q_{gw_t} is the total quantity of groundwater extracted. We assume that farmers maximize their net benefits by first exhausting the total fixed allocation of surface water in the canal commands before extracting groundwater to meet irrigation deficits.

We further assume that there are two heterogeneous types of farmers—sharecroppers and owner cultivators—with an identical production function. The water demand function $q(p_t) = \frac{a_0}{a_1} - \frac{p_t}{a_1}$ can be disaggregated into separate water demand functions for owner cultivators and for sharecroppers: $q^{oc}(p_t) = \delta\left(\frac{a_0}{a_1} - \frac{p_t}{a_1}\right)$ and $q^{sc}(p_t) = (1-\delta)\left(\frac{a_0}{a_1} - \frac{p_t}{a_1}\right)$, where the superscripts oc and sc denote owner cultivators and sharecroppers, respectively, δ is the share of land cultivated by owner cultivators, and $(1-\delta)$ is the share of land cultivated by sharecroppers. These are demand functions for irrigation water (a homogenous input) and should not be confused with the demand for a homogenous output. The inverse water

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[1] In our empirical setting (Sindh), annual surface water allocations are fixed and tied to farm-size. Therefore, we treat surface water supplies as an exogenous parameter.

demand functions for owner cultivators and sharecroppers are given by:

$$p^{oc}(q_t) = a_0 - \frac{a_1}{\delta} q_t \tag{1}$$

$$p^{sc}(q_t) = a_0 - \frac{a_1}{(1-\delta)} q_t \tag{2}$$

The total amount of surface water withdrawals (q_{sw}) are equal each year and divided among owner cultivators and sharecroppers according to their respective land shares, which gives $q_{sw}^{oc} = \delta q_{sw}$ and $q_{sw}^{sc} = (1-\delta) q_{sw}$.

Following the literature (Esteban and Albiac 2011; Knapp and Baerenklau 2006; Laukkanen and Koundouri 2006), we assume a constant marginal extraction cost function, which linearly depends on the depth from which farmers extract groundwater:

$$m'\left(q_{gw_t}\right) = \gamma (h_l - h_t) \tag{3}$$

where $m'\left(q_{gw_t}\right)$ is the marginal extraction cost in $\mathrm{Rs\,m^{-3}}$ in time period t; γ is the marginal cost of extraction per unit of lift in $\mathrm{Rs\,m^{-3}\,m^{-1}}$, which shows the marginal cost of extracting a cubic meter of groundwater from a depth of 1 m; h_l is the surface elevation in m; and h_t is the water table height (the distance from the bottom of the aquifer to the surface of the water table) in m. The difference between the surface elevation and the water table height $(h_l - h_t)$ is the depth from which farmers extract groundwater. The function $\gamma (h_l - h_t)$ therefore represents the marginal extraction cost of a cubic meter of groundwater from a depth of $(h_l - h_t)$ m.

A constant marginal extraction cost function implies that the total groundwater pumping cost is linear in extractions (q_{gw_t}). The linear total cost function has the desirable properties of having a positive partial derivative with respect to q_{gw_t} and a negative cross-partial derivative between q_{gw_t} and the water table height h_t. The respective groundwater extractions for owner cultivators and sharecroppers are $q_{qw_t}^{oc}$ and $q_{gw_t}^{sc}$.

Given the above functions and definitions, owner cultivators' net benefits from irrigated agriculture are:

$$\pi_t^{oc} = \int_0^{(1-\beta_{sw})q_{sw}^{oc}+q_{gw_t}^{oc}} p^{oc}(q_t)\,\mathrm{d}q_t - \int_0^{q_{gw_t}^{oc}} m'\left(q_{gw_t}\right)\mathrm{d}q_{gw_t} \tag{4}$$

Equation 4 defines owner cultivators' net benefits as the difference between their total revenue from irrigated agriculture and their total groundwater extraction cost.

Given the terms of their tenurial contracts, sharecroppers must provide a portion of their output to their landlords who in turn bear a portion of their sharecroppers' input costs. Let $f \in [0,1]$ represent the landlords' share of their sharecroppers' total revenue and $v \in [0,1]$ represent the share of the sharecroppers' total groundwater costs borne by their landlords. This implies that sharecroppers' net benefits from irrigated agriculture are:

$$\pi_t^{sc} = (1-f)\int_0^{(1-\beta_{sw})q_{sw}^{sc}+q_{gw_t}^{sc}} p^{sc}(q_t)\,\mathrm{d}q_t - (1-v)\int_0^{q_{gw_t}^{sc}} m'\left(q_{gw_t}\right)\mathrm{d}q_{gw_t} \tag{5}$$

The first term of the right-hand side of equation 5 represents sharecroppers' own share of their revenue from irrigated agriculture while the second term represents sharecroppers' own share of their total pumping cost.

Groundwater extractions in the current period depend on the state of the water table height in the current period and affect the state of the water table height in the following period. The water table height evolves over time according to the following equation of motion:

$$h_{t+1} = h_t + \frac{\beta_{sw}q_{sw} + \beta_{dp}\left((1-\beta_{sw})q_{sw} + q_{gw_t}^{oc} + q_{gw_t}^{sc}\right) - q_{gw_t}^{oc} - q_{gw_t}^{sc}}{As_y} \tag{6}$$

where β_{dp} is the coefficient of deep percolation, which measures the percentage of irrigation water (surface water and groundwater) that seeps into the aquifer after farmers apply it to their fields; and β_{sw} is the percentage of surface water that seeps into the aquifer during delivery from the canals level to the fields.

Equation 6 shows that over time the seepage from canal water delivery and deep percolation from irrigation cause the water table to rise while groundwater extractions cause the water table to fall. The water table height and groundwater extractions are in steady state (or equilibrium) when $h_{t+1} - h_t = 0$. If extractions ($q^{oc}_{gw_t} + q^{sc}_{gw_t}$) are greater than their steady-state level, they exceed aquifer recharge, and the water table height falls in the next period. If extractions are less than their steady-state level, aquifer recharge exceeds extractions, and the water table level rises in the next period.

Owner cultivators and sharecroppers face a common water table height in each period. Since the marginal extraction cost for both owner cultivators and sharecroppers is constant and a function of the water table height, the decrease in the water table height due to extractions increases the total pumping cost for both types of farmers. This results in progressively lower extractions.

2.2 Decision Rules

Using the functional forms for the net benefits of owner cultivators and sharecroppers and the equation of motion of the water table height described above, we develop decision rules for an open access regime and for optimal management.

2.2.1 Open Access Regime

Under an open access regime (the status quo in Sindh), farmers neglect the effect of their groundwater extractions in the present period on the state of the aquifer in the future. Owner cultivators and sharecroppers choose decision variables to maximize annual net benefits in each year given the current value of the state variable, disregarding the future states of the aquifer. The objectives (profit maximization) of owner cultivators and sharecroppers in period t are:

$$\begin{aligned} &\max_{q^{oc}_{gw_t}} \pi^{oc}_t\left(h_t, q^{oc}_{gw_t}\right) \\ &\max_{q^{sc}_{gw_t}} \pi^{sc}_t\left(h_t, q^{sc}_{gw_t}\right) \end{aligned} \tag{7}$$

Each maximization problem in equation 7 is solved subject to the boundary and non-negativity constraints $q^{oc}_{gw_t} \geq 0$, $q^{sc}_{gw_t} \geq 0$, and $0 \leq h_t \leq h_l - h_{rz}$, where h_{rz} is the depth to the root zone. The constraint on h_t ensures that the water table level is positive and that it remains below the root zone—water table level above the root zone leads to waterlogging.

The first-order conditions, after dropping the time subscript, are:

$$p^{oc} = m^{'} \tag{8}$$

$$p^{sc} = \frac{(1-v)}{(1-f)} m^{'} \tag{9}$$

The owner cultivators' first-order condition equates their marginal revenue from irrigated agriculture with their marginal extraction cost. However, in the sharecroppers' case, the first-order condition equates their marginal revenue with their marginal extraction cost scaled by the factor $\frac{(1-v)}{(1-f)}$. When $f > v$, we have $\frac{(1-v)}{(1-f)} m^{'} > m^{'}$, which implies that for an equal amount of land cultivated by each type of farmer, sharecroppers' open access extractions are lower than those of owner cultivators—the source of the Marshallian inefficiency. When $f = v$, sharecroppers' and owner cultivators' open access extractions are equal, and the Marshallian inefficiency disappears.

However, equal revenue and cost shares are not often observed in practice. As the institutional literature (Braverman and Stiglitz 1986) shows, when labor effort is inelastic in response to the cost share, landlords maximize the rents extracted from sharecroppers by setting $f > v$. To see discernible differences in the input intensity of sharecroppers and owner cultivators, we impose Marshallian inefficiency in the model by assuming that landlords set $f > v$ under a sharecropping contract. Moreover, sharecropping contracts in Sindh often have long-term tenure, with some farmers cultivating the same lands under a sharecropping agreement their entire lives (Hussain et al. 2004). We assume that sharecroppers are locked in lifelong contracts so that the Marshallian inefficiency persists indefinitely.

Equations 8 and 9 show that under open access, sharecropping leads to lower groundwater extractions in each period vis-à-vis Marshallian inefficiency compared to the counterfactual model in which all farmers are owner cultivators. If the combined extractions of owner cultivators and sharecroppers exceed aquifer recharge, the water table level drops, raising next period's marginal extraction costs. Owner cultivators' and sharecroppers' extractions fall each subsequent period as their marginal extraction costs rise. Given sharecroppers' reduced water intensity relative to owner cultivators, we expect our sharecropping model to generate a higher water table height—and consequently higher annual net benefits because of cheaper extractions—through time compared to the counterfactual model with only owner cultivators.

The first-order conditions above are linear in extractions and the state variable. We solve them to find the profit-maximizing levels of owner cultivators' and sharecroppers' groundwater extractions as functions of the state variable. Starting from the initial (base period) values of the state variable (h_0), we simulate the results forward using the equation of motion of the water table height.

2.2.2 Optimal Management

Under optimal management, a social planner maximizes the present value of net benefits over multiple time periods subject to the equation of motion of the state variable and the boundary and non-negativity constraints specified earlier. Groundwater extractions under optimal management depend not only on the current level of the water table height but also on the discounted value of the impact of current extractions on future net benefits.

We solve the problem using dynamic programming in which the value function (optimized objective function) is given by:

$$V(h_0) = \max_{q_{gw_t}^{oc}, q_{gw_t}^{sc}} \left\{ \sum_{t=0}^{\infty} \alpha^t \left(\pi_t^{oc} + \pi_t^{sc}\right) \right\} \tag{10}$$

The value function V (after dropping the time subscript) must satisfy Bellman's equation of the form:

$$V(h) = \max_{q_{gw}^{oc}, q_{gw}^{sc}} \left\{ \pi\left(h, q_{gw}^{oc}, q_{gw}^{sc}\right) + \alpha V\left(g\left(h, q_{gw}^{oc}, q_{gw}^{sc}\right)\right) \right\} \tag{11}$$

where $\pi = \pi^{oc} + \pi^{sc}$ represents owner cultivators' and sharecroppers' combined annual net benefits defined in terms of the water table height and extractions, and g is a function that presents the water table height in the next period as a function of the current values of the state variable and extractions. The equation of motion of the water table height (equation 6) defines the function g. The optimization is subject to the same boundary and non-negativity constraints as the profit maximization problem under the open access regime.

The Euler equilibrium conditions that define the solution to the Bellman equation (11) are:

$$p^{oc} = m' + \frac{\alpha(1-\beta_{dp})}{As_y} \frac{\partial V}{\partial h} \tag{12}$$

$$p^{sc} = \frac{(1-v)}{(1-f)} m' + \frac{\alpha(1-\beta_{dp})}{(1-f)As_y} \frac{\partial V}{\partial h} \tag{13}$$

$$\frac{\partial V}{\partial h} = \gamma q_{gw}^{oc} + \gamma(1-v) q_{gw}^{sc} + \alpha \frac{\partial V}{\partial h} \tag{14}$$

Equations 12 and 13 show that owner cultivators' and sharecroppers' optimal extraction paths through time balance their marginal revenues from extractions against the sum of their marginal extraction costs and their marginal user costs—the discounted value of forgone future net benefits owing to a unit of extraction in the present (in situ value of the resource stock)—in each period. The term $\frac{(1-\beta_{dp})}{As_y} \frac{\partial V}{\partial h}$ shows the marginal effect of a change in the water table height on future net benefits through time—the pumping cost externality. The size of this externality depends on the deep percolation parameter (β_{dp}) and the capacity of the aquifer (As_y)—the externality increases as β_{dp} or As_y fall. Equation 14 represents the non-reduced form shadow price of the water table height.

The Euler conditions above demonstrate that both owner cultivators and sharecroppers internalize the temporal pumping cost externality under optimal management in contrast to the open access case. The externality has an unambiguous impact on farmers' extractions through time: it incentives farmers to reduce extractions in the present to benefit from lower extraction costs in future periods. We expect lower extractions and a higher water table level through time under optimal management than under open access. This difference in the state of the aquifer translates into welfare gains of moving from open access to optimal management.

Comparing equations 12 and 13, we can see that sharecroppers' marginal extraction cost and marginal user cost are scaled by the factors $\frac{(1-v)}{(1-f)}$ and $\frac{1}{(1-f)}$, respectively, which represent the Marshallian inefficiency. Given our earlier assumption that $f > v$, sharecroppers face a higher opportunity cost of extractions relative to owner cultivators. Therefore, we expect sharecroppers to have a lower optimal extraction path through time. Similar to the open access case, this implies that the sharecropping model in the optimal management case would yield a higher water table level through time compared to the counterfactual model with only owner cultivators. The trajectory of the annual net benefits under the sharecropping model will exceed the trajectory under the counterfactual model when the gains from realizing a larger resource stock dominates the benefit of a higher extraction rate. We cannot unequivocally determine the difference in these trajectories without parametrizing the model.

The dynamic programming problem above consists of solving the Bellman equation (11) for the unknown value function V and optimal extractions as functions of the state variable. We use an iterative algorithm (value function iteration) consistent with the dynamic programming literature (Judd 1998) to approximate the value function and solve for the optimal extraction paths.

We first discretize the unidimensional state space and initiate the algorithm by assuming an estimate of the value function—our initial estimate for the value function is zero across the state space. We insert this estimate into the right-hand side of the Bellman equation and solve the control optimization problem in 11 for the entire state space. Using a bicubic spline, we then approximate a smooth value function, which we use as an estimate for the next round of iteration. We repeat the process until the algorithm converges, yielding the optimized value function and the state-dependent optimal decision rules.

We use *Mathematica 12* to solve and compute our results for the maximization problem in the open access case and the dynamic programming problem in the optimal management case.

3 Data and Calibration

In this section, we first describe the data from Pakistan's Sindh province and then use it to calibrate the extraction model developed earlier. The primary reason we chose Sindh as our empirical setting is that the province is one of the few areas characterized by groundwater irrigation and sharecropping with sufficient data to conduct our simulation exercise. Sindh has the highest share of sharecroppers (34 percent) compared to the other provinces of the country while its farmers irrigate 28 percent of its total agricultural land with open access groundwater from an unconfined freshwater aquifer. Sindh is also Pakistan's second largest agricultural province in terms of contribution to GDP but faces serious irrigation challenges in the form of dwindling water supplies (Briscoe et al. 2006). Sindh's economic importance and policy conditions make it an ideal setting to test our model.

3.1 Data

Table 1 shows the values of the parameters used to simulate the baseline model. We use the agricultural year 2013-2014 as the base year (initial period) of the model. We convert all rupee values taken from other sources to 2013 values using Consumer Price Index data from the IMF's International Financial Statistics (International Monetary Fund 2015).[2]

We calibrate the values of the intercept (a_0) and the slope (a_1) of the water demand function using data from Sindh Development Statistics 2014 (Government of Sindh 2014), Pakistan Agriculture Census 2010-2011 (Government of Pakistan 2012), and Pasha (2015). We

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[2] One US dollar exchanged for 101.6 Pakistani rupees on average in 2013.

describe the calibration process in the subsection that follows.

We take the value of: the marginal cost of extraction of groundwater per unit of lift (γ) from Qureshi, McCornick, and Sharma (2010); the coefficient of surface water seepage into the aquifer (β_{sw}) and deep percolation of applied irrigation water (β_{dp}) from van Steenbergen, Basharat, and Lashari (2015); the area of the aquifer (A), the average initial water table height (h_0) in the base year, and the average surface elevation (h_l) from Shahab et al. (2019); and the specific yield (s_y) from Bonsor et al. (2017).

The shares of owner cultivators (δ) and sharecroppers ($1-\delta$) are 0.67 and 0.33, respectively (Jacoby and Mansuri 2009). We use $f = 0.75$ and $v = 0.25$ as the values of the shares of the landlords' output and groundwater cost, which are observed as common values in agricultural data from Sindh (Pakistan Rural Household Survey I and II) and are sufficient to induce Marshallian inefficiency in the optimization behavior of sharecroppers. The base-year values of total net benefits (π_0), surface water supplies (q_{sw}), and groundwater extractions (q_{gw_0}) are Rs112.5 billion (Pasha 2015), 11.25 Bm^3 (Government of Sindh 2014), and 6 Bm^3 (Government of Sindh 2013), respectively.

Several previous studies have used the real interest rate as a proxy for the discount rate. Data shows that Pakistan has historically faced a low real interest rate—even negative in some years—owing to high rates of inflation (International Monetary Fund 2015). Using the real interest rate to discount future net benefits would not suffice in our case. In low-income rural settings such as ours, farmers are highly credit constrained, lack safety nets to buffer production shocks (absence of agricultural insurance), and have myopic internal time preferences. These factors lead farmers to exhibit high discount rates—as high as over 100 percent in some extreme cases—as confirmed by several experimental studies (Duquette, Higgins, and Horowitz 2011; Frederick, Loewenstein, and O'donoghue 2002; Pender 1996). In the absence of experimentally determined time preferences for farmers in our setting, we assume a discount rate (d) of 10 percent, which is several magnitudes higher than the average real interest rate in Pakistan in the period 2004-2013 (0.6 percent). The discount factor (α) is given by $\frac{1}{1+d}$.

3.2 Water Demand Function Calibration

In the model, we have assumed that the landlords' share of output is greater than their share of input costs, which leads to Marshallian inefficiency expressed as reduced input intensity by sharecroppers. We calibrate the water demand function to account for the differences in the optimization behavior of sharecroppers and owner cultivators. The first-order conditions of profit maximization under an open access regime (equations 8 and 9) implicitly define the total optimal extractions ($q^{*}_{gw_t} = q^{oc^*}_{gw_t} + q^{sc^*}_{gw_t}$) as a function of the unknown water demand function parameters a_0 and a_1. We obtain the values of these parameters by computationally solving the system of equations defined by the two first-order conditions and the annual net benefits ($\pi_t = \pi^{oc}_t + \pi^{sc}_t$) using the observed base-year values of all the parameters and variables. This yields: $a_0 = 19.15$ Rs and $a_1 = 1.19$ Rs Bm^{-3}.

The annual net benefits π_t are a function of the control variables $q^{oc}_{gw_t}$ (quantity of groundwater extracted by owner cultivators) and $q^{sc}_{gw_t}$ (quantity of groundwater extracted by sharecroppers) and the state variable h_t (height of the water table). We solve the model using the decision rules regarding the open access and optimal management regimes described earlier. We refer to this model as the tenure model ($\delta = 0.67$) and compare it to the baseline model (the counterfactual) in which all farmers are owner cultivators ($\delta = 1$).

4 Results

In this section, we discuss the results of the tenure model and the baseline model. We have simulated the results with a time horizon of 100 years—over 99 percent of the convergence towards the steady state occurs within this period. Figures 1 and 3 present the dynamics of groundwater extractions, the water table height, and annual net benefits under open access and under optimal management for the tenure model and the baseline model. Table 2 provides a summary of the key results.

4.1 Open Access

As expected, groundwater extractions under open access given by the tenure model are lower than the extractions given by the baseline model. In the tenure model, sharecroppers have a lower input intensity because of the Marshallian disincentive and consequently extract less groundwater than owner cultivators. Extractions exceed aquifer recharge in each period and the water table level falls through time. Since the marginal extraction cost is increasing in water table depth, extractions fall as it becomes costly to pump groundwater from increasing depths. This decreases total revenue from extractions and raises total extraction costs, leading to a fall in the annual net benefits through time.

In the tenure model, owner cultivators' extractions are higher than sharecroppers' extractions in each period not only because of the Marshallian inefficiency but also because the tenure model weights owner cultivators' extractions more than sharecroppers' extractions—where the weights represent the shares of total land under owner cultivation and under sharecropping. We can obtain the pure effect of the Marshallian inefficiency by normalizing extractions of owner cultivators and sharecroppers by their respective weights. The open access first-order conditions (equations 8 and 9) reveal that the difference between the extractions of sharecroppers and owner cultivators increases linearly with extraction depth. After normalizing, sharecroppers' extractions are 9.5 percent lower than owner cultivators' extractions in the initial period; this difference increases to almost 70 percent at steady state.

Owing to the differences in extractions, the water table height given by the tenure model falls more gradually compared to the baseline model. The difference in the water table heights reaches a maximum value of 6.4 m at steady state. This divergence in the groundwater stock at steady state—with a higher stock under the tenure model—translates into 2.6 percent higher annual net benefits and 2.3 percent higher undiscounted aggregate net returns under the tenure model. This result demonstrates that despite its inherent inefficiency, sharecropping can improve social welfare in the long run.

4.2 Optimal Management

As expected, optimal extractions given by the tenure model are lower than the optimal extractions given by the baseline model–the difference in extractions is higher under optimal management than under open access. In the tenure mode, the Marshallian inefficiency distorts not only sharecroppers' marginal extraction cost but also their marginal user cost—the discounted value of the forgone net benefits from pumping groundwater in the present—relative to owner cultivators, as shown by the Euler conditions (equations 12, 13, and 14). After normalizing optimal extractions of sharecroppers and owner cultivators by their respective shares of land under cultivation, we observe a large percentage difference between the optimal extractions of sharecroppers and owner cultivators in the initial period (76 percent). This difference gradually rises to 79 percent in steady state.

Optimal extractions exceed aquifer recharge in each period, leading to a gradual fall in the water table height over time. The annual net benefits follow the same qualitative trajectory as optimal extractions—they fall over time as the lower stock of groundwater raises total extraction costs and decreases total revenue from extractions.

The difference between the optimal extractions of sharecroppers and owner cultivators leads to a higher water table through time under the tenure model compared to the baseline model. The water table level under the tenure model is 9.7 m higher at steady state. This divergence in the groundwater stock across the two models represents a difference of 3.1 percent in their steady state annual net benefits. In aggregate, the tenure model yields 2.8 percent higher undiscounted net returns over the baseline model. Similar to the open access case, the optimal management results reveal that the prevalence of sharecropping can increase long-run social welfare. This creates tension for policy makers focused on increasing landownership as a means to enhance social welfare in the area.

4.3 Welfare Gains of Optimal Management

Optimal extractions under both the tenure model and the baseline model are lower than their respective open access extractions through time, which improves the state of the aquifer. The optimal extraction decision depends on the current and the future values of the state variable—

lower extractions in the present implies greater future net returns from a higher water table level.

The total undiscounted welfare gains of shifting from open access to optimal management are 4.93 percent under the tenure model and 4.43 percent under the baseline model. We further examine the distribution of welfare gains across sharecroppers and owner cultivators in the tenure model. Even though sharecroppers cultivate 34 percent of the land in our study area, they accrue only 7 percent of the total welfare gains of moving from open access to optimal management—owner cultivators accrue the remaining 93 percent. This shows that although sharecropping improves the groundwater stock under optimal management relative to the baseline, sharecroppers receive a disproportionately lower share of the welfare gains of optimal management.

When considering the present values of future net benefits, the welfare gains from optimal management drop to 1.23 percent and 1.07 percent under the tenure model and the baseline model, respectively. This implies that our results exhibit the Gisser-Sanchez effect consistent with the previous literature on groundwater extractions. Although our discounted welfare gains seem modest, they are larger than the gains estimated by Nieswiadomy 1985 (0.28 percent) and Lee, Short, and Heady 1981 (0.3 percent), and close to the estimates of Merrill and Guilfoos 2018 (2.88–3.01 percent), Koundouri and Christou 2006 (3.8 percent), Knapp and Olson 1995 (2.6 percent), and Kim et al. 1989 (1–3.7 percent). The results serve as a benchmark for policymakers interested in aquifer management and the distribution of social welfare gains across owner cultivators and sharecroppers in our study area.

4.4 Sensitivity Analysis

Our estimates for the returns to optimal management are sensitive to values of the model parameters, especially the discount rate. We expect the welfare gains to increase at lower discount rates. We also expect the welfare gains to respond to changes in the tenancy parameters since the results of the tenure model show that returns to optimal management are higher under Marshallian inefficiency. We conduct a sensitivity analysis to examine the response of our results to changes in the values of the model parameters, which include the tenancy land share (δ), landlords' revenue share (f) and cost share (v), the discount rate (d), surface water supplies (q_{sw}), marginal extraction cost per unit of lift (γ), and the intercept of the water demand function (a_0). To keep the analysis succinct, we perform the sensitivity analysis on the parameters of only the tenure model—the sensitivity analysis of the parameters of the baseline model is qualitatively similar.

Table 2 provides the results of the sensitivity analysis of the tenure parameters. The effect of the Marshallian inefficiency on sharecroppers' extractions increases when the share of land cultivated by owner cultivators is lower than the share of land cultivated by sharecroppers ($\delta = 0.34$ and $1—\delta = 0.66$). Compared to the initial tenure model, this leads to a larger stock of groundwater over time under both open access and optimal management. Optimal extractions in the initial period fall to the lowest possible level required to maintain the maximum water table height (45 m), leading to a constant stock of groundwater through time. As a result, the welfare gains from optimal management rise to 1.59 percent. When sharecroppers receive more favorable revenue and cost share terms ($f = 0.25$ and $v = 0$), the effect of the Marshallian inefficiency diminishes and the returns to optimal management fall to 0.84 percent.

Table 3 shows the results of the sensitivity analysis of a set of economic and hydrological parameters. At a 50 percent lower discount rate ($d = 0.05$), the present value of net benefits through time increase as expected and the returns to optimal management rise to 2.41 percent—an increase of 96 percent over the welfare gains under the initial tenure model. When the surface water supplies fall by 10 percent ($q_{sw} = 10.13\,\mathrm{Bm}^3$), the stock of groundwater under open access falls rapidly as farmers meet their irrigation deficits through greater groundwater extractions. As a result, the scarcity value of groundwater rises and the returns to optimal management increase to 1.41 percent.

For a 25 percent increase in the marginal extraction cost per unit of lift ($\gamma = 0.086\,\mathrm{Rs\,m^{-3}\,m^{-1}}$), open access and optimal extractions are lower than those given by the initial tenure model. The optimal extractions are low enough to maintain the maximum water table height in each period and the welfare gains from optimal management increase to 1.55 percent. In the final sensitivity analysis, we increase the value of the intercept of the water demand function by 10 percent ($a_0 = 21.07$ Rs), which represents a higher willingness to pay for each unit of irrigation water. The higher marginal value for water incentivizes greater extractions, causing a reduction in the groundwater stock under both open access and optimal management. However, the higher value of water also translates into greater total returns to irrigation, which more than offsets the cost of a lower groundwater stock, and the welfare gains of optimal management increase to 1.40 percent.

5 Policy Instruments and Implications

The results in the previous section demonstrate the quantitative benefits associated with optimal management of groundwater in our setting. However, the results so far do not identify how policymakers can incentivize optimal groundwater extractions. Under an open access regime, farmers do not consider the implications of the uncontrolled level of extractions and fail to internalize the resulting externality: a fall in the water table level (reduction in the groundwater stock). Policy interventions have to address this externality by appropriately constraining total groundwater extractions in each period.

We recognize that effective groundwater management and governance is a complex task that depends on social, political, institutional, and economic factors. As case studies and experiences from around the world show, groundwater governance carries no simple solutions. Experts must adapt groundwater policies according to the socio-political environment of a particular region (Shah 2014). As an extension of the above analysis, we derive price levels that could lead to the attainment of the optimal state of the aquifer across time, and we discuss policy tradeoffs.

A command-and-control policy such as a quota system allows the regulator to set limits on groundwater extractions in each period. Unlike a quota on extractions, a charge on per unit extractions leads farmers to adjust behavior so that the marginal benefit of an additional unit of extraction is equal to the per unit charge. Farmers' ability to adjust extractions when faced with a charge leads to a cost-effective response in a heterogeneous environment. To ensure that extractions remain at the optimal level, the regulator has to solve for the optimal per unit charge.

Suppose that the regulator sets a price τ_t on each unit of groundwater extraction in period t. In a decentralized open access environment, where a charge can be levied on extractions, producers maximize $\pi\left(h_t, q_{gw_t}\right) - \tau_t q_{gw_t}$. The first-order condition is:

$$\frac{\partial \pi}{\partial q_{gw_t}} = \tau_t \tag{15}$$

The first-order condition implies that farmers adjust their extractions so that the marginal benefit of an additional unit of extraction equals the additional cost of that unit of extraction (the charge per unit of extraction). Given the Bellman equation (11), a regulator maximizes $\pi\left(h_t, q_{gw_t}\right) + \alpha V\left(h_{t+1}\right)$ for optimality, where V is the value function, and the future values of the state variable are calculated using the equation of motion of the water table height. The solution of the optimal extractions is characterized by the following first-order condition:

$$\frac{\partial \pi}{\partial q_{gw_t}} = \frac{\alpha\left(1-\beta_{dp}\right)}{As_y}\frac{\partial V}{\partial h_{t+1}} \tag{16}$$

Comparing equations (15) and (16) shows that the optimal price is:

$$\tau_t = \frac{\alpha\left(1-\beta_{dp}\right)}{As_y}\frac{\partial V}{\partial h_{t+1}} \tag{17}$$

Note that $\frac{\partial V}{\partial h_{t+1}} > 0$ since an increase in the water table height leads to greater future net benefits.

Figure 3 shows the time series path of the optimal price under the baseline and tenure models. The trajectory qualitatively follows the time series path of the optimal extractions. The price through time is decreasing in the water table depth since the benefit of a marginal fall in the water table level decreases with the extraction rate.

The optimal price under the tenure model is lower than the optimal price under the baseline model in each period, reflecting the lower scarcity value of groundwater under the tenure model. The explanation for this stems from the qualitative difference between the optimal extraction rates of the two types of farmers. Sharecroppers have a lower optimal extraction rate compared to owner cultivators owing to Marshallian inefficiency, leading to a larger groundwater stock through time in the tenure model. Since Marshallian inefficiency improves groundwater stock in each period, sharecroppers' marginal value of maintaining a higher water table level in the present—to reduce pumping costs in future periods—is lower than that of owner cultivators. Therefore, the tenure model generates a lower optimal extraction price than the baseline model.

In the initial period, the optimal price under the tenure model is Rs1.32 per m^3. From the initial period to the steady state, the aggregate revenue from the groundwater charge is 4.3 percent of the aggregate net returns. Owner cultivators contribute 90 percent to the total aggregate revenue generated by the groundwater charge—sharecroppers contribute the remaining 10 percent, which is lower than the proportion of land under sharecropping. Thus, while owner cultivators receive a much larger share of the gains from optimal management, they also bear a considerably share of the optimal charge compared to sharecroppers.

The optimal groundwater price varies with time and requires annual revisions to induce optimal extractions through time. Given the high transaction costs of planning, setting a price equivalent to the average of the optimal price for five- or ten-year periods might prove more practical than revising the price on a yearly basis. To ensure equity, the regulator must redistribute the revenue from a charge scheme to the water users. Drawing away this revenue from the sector can lead to negligible benefits from optimal management—even lower than benefits under open access (Feinerman and Knapp 1983).

A successful implementation of the groundwater charge scheme requires the regulator to redistribute the revenue to water users in a manner that does not incentivize extractions beyond the optimal level. Rebating farmers for the adoption of efficient irrigation technologies and cultivation of high-value and less water-intensive crops can facilitate optimal extractions. An important caveat here is that subsidizing efficient irrigation technologies could induce greater extractions through the "rebound effect," especially if farmers start intensively cultivating current land or increase land under cultivation (Berbel and Mateos 2014; Song et al. 2018). The regulator can also invest the charge revenue in modernization of the existing infrastructure for surface water supplies (assuming their availability), allowing farmers an option to reliably substitute away from groundwater.

6 Conclusion

Land tenure heterogeneity in the form of owner cultivation and sharecropping can affect resource extraction decisions. The classical literature on land tenure has shown that sharecroppers exhibit Marshallian inefficiency, which reduces their input intensity compared to owner cultivators. The impact of Marshallian inefficiency on the extraction of resources such as groundwater has serious implications for sustainable resource use in several agricultural settings where farmers still heavily practice sharecropping. To investigate the effects of land tenure heterogeneity on resource use, we introduced differences in behavior across owner cultivators and sharecroppers in a dynamic groundwater extraction problem. By calibrating the model with data from Pakistan's Sindh province, we analyzed the long-run dynamics of extractions, the state of the aquifer, and net benefits under two types of management regimes: open access and optimal management.

Including land tenure heterogeneity in the groundwater extraction problem showed mixed results for aquifer sustainability and resource management. Under both regimes (open access and optimal management), we observed significant differences in the long-run dynamics of groundwater extractions and the water table level between the tenure model (33 percent sharecroppers and 67 percent owner cultivators) and the baseline model (100 percent owner cultivators). The water table level and hence the net benefits through time were higher under the tenure model in both the open access case and the optimal management case. The results were sensitive to changes in parameters of the model, especially the discount rate, the share of land cultivated by sharecroppers, and sharecroppers' revenue and cost shares. Price-based policies such as optimal water charges offer an effective tool to manage aquifers in agricultural settings with land under sharecropping.

In future work, we can further explore resource dynamics in relation to land tenure by introducing strategic rivalry in groundwater extractions between owner cultivators and sharecroppers. In a game of strategic substitutes, an increase in groundwater extractions by one player (either owner cultivators or sharecroppers) could reduce the marginal benefit of groundwater extractions of the opposing player. We can determine the optimal extraction paths by simultaneously solving the best-response functions of both players. The strategic response of each player (the optimal groundwater extraction path) would depend on the price elasticity of irrigation water.

We can also apply the model developed in this paper to aquifers in countries with a large share of sharecroppers—for example, India and Sub-Saharan Africa. The results of the model when applied to these locations could yield important insights for designing groundwater regulatory policies since the effect of the Marshallian inefficiency on groundwater extractions varies with the prevalence of sharecropping. As the literature on groundwater management in developing economies moves forward, it increasingly needs to account for the impact of institutional arrangements, such as sharecropping, on extractions and aquifer sustainability in order to inform more effective policies.

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Tables

Table 1: Model Parameters

Parameter	Description	Value
a_0	Intercept of the water demand function	19.15 Rs
a_1	Slope of the water demand function	$1.19\,\mathrm{Rs\,Bm^{-3}}$
γ	Marginal cost of extraction of groundwater per unit of lift	$0.07\,\mathrm{Rs\,m^{-3}\,m^{-1}}$
β_{sw}	Coefficient of surface water seepage into the aquifer	0.15
β_{dp}	Deep percolation	0.15
q_{sw}	Surface water withdrawls	$11.25\,\mathrm{Bm^3}$
A	Area of the aquifer	$7.5\,\mathrm{Bm^2}$
s_y	Specific yield	0.20
h_l	Surface Elevation	50 m
h_{rz}	Depth to root zone	5 m
h_0	Initial water table height	45 m
δ	Share of owner cultivators	0.66
f	Landlords' share of their sharecroppers' total revenue	0.75
v	Landlords' share of their sharecroppers' total extraction costs	0.25
α	Discount factor	0.91

Table 2: Summary of Results and Sensitivity Analysis (Tenure Parameters)

	Baseline Model		Tenure Model		SA1 ($\delta = 0.34$)		SA2 ($f = 0.25$; $v = 0$)	
	OA	OM	OA	OM	OA	OM	OA	OM
First 25 Years								
Groundwater Extractions (Bm^3)	4.46	3.96	4.26	3.71	3.98	3.67	4.68	4.17
Water Table Height (m)	25.21	38.78	27.34	44.15	31.58	45.00	22.27	34.94
Annual Net Benefits (Billion Rs)	105.25	108.90	106.59	110.74	71.90	74.90	129.79	133.35
First 100 Years								
Groundwater Extractions (Bm^3)	3.70	3.69	3.68	3.67	3.67	3.67	3.73	3.72
Water Table Height (m)	15.38	34.29	21.48	43.67	29.30	45.00	7.76	26.32
Annual Net Benefits (Billion Rs)	102.45	107.34	105.03	110.57	71.37	74.90	125.52	130.36
Discounted Total Net Benefits at Steady State (Billion Rs)	1090.17	1101.82	1095.49	1108.95	737.27	748.99	1343.67	1354.98
Welfare Gains from Optimal Management (Percent)	1.07		1.23		1.59		0.84	

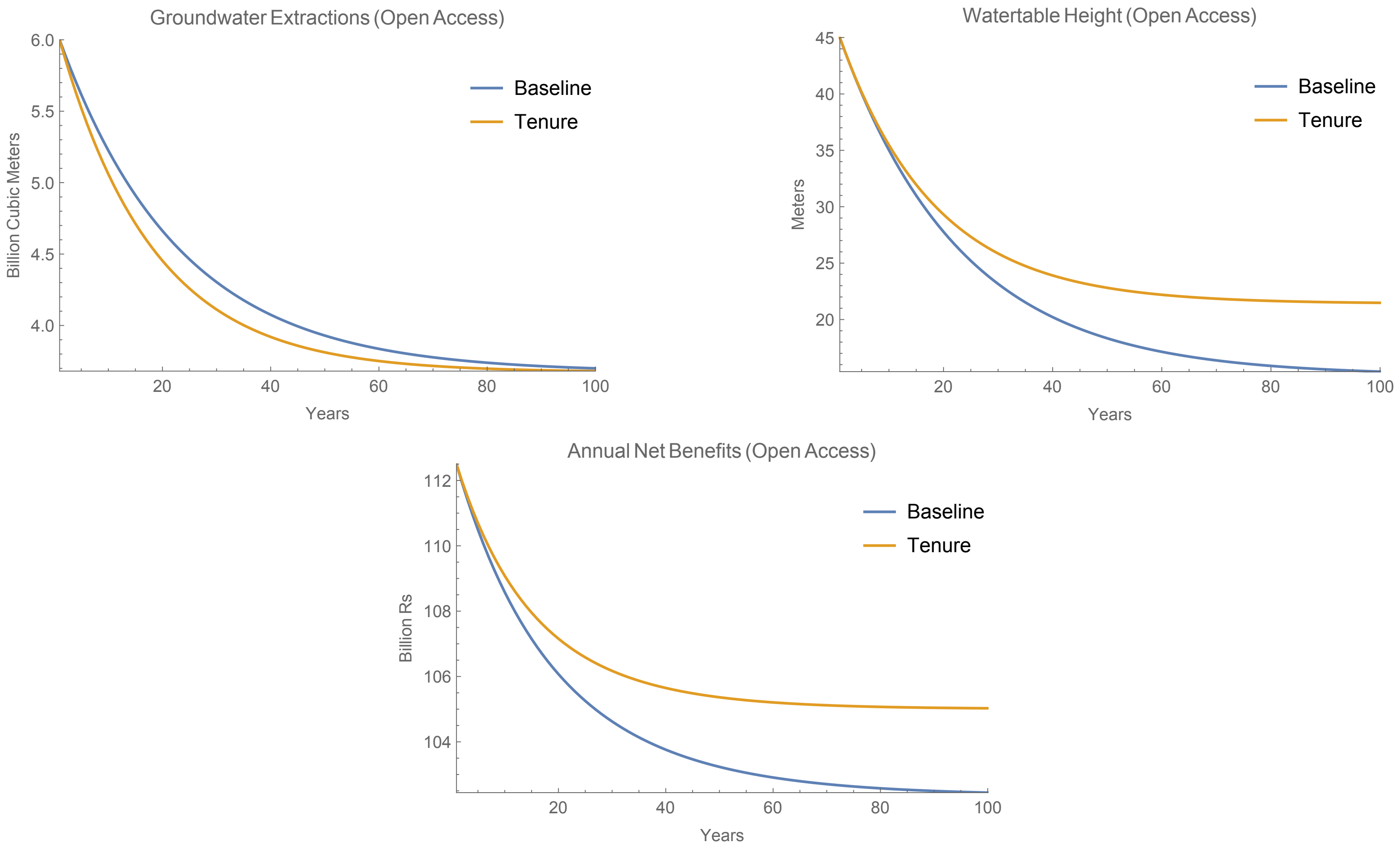
Note: OA = Open Access; OM = Optimal Management; SA1 (Sensitivity Analysis 1): owner cultivators' land share (δ) = 0.34; SA2 (Sensitivity Analysis 2): landlords' revenue share (f) = 0.25 and landlords' input cost share (v) = 0.

Table 3: Sensitivity Analysis (Economic and Hydrological Parameters)

	SA3 ($d = 0.05$)		SA4 ($q_{sw} = 10.13$)		SA5 ($\gamma = 0.086$)		SA6 ($a_0 = 21.07$)	
	OA	OM	OA	OM	OA	OM	OA	OM
First 25 Years								
Groundwater Extractions (Bm^3)	4.26	3.67	4.22	3.72	4.06	3.67	4.66	4.12
Water Table Height (m)	27.34	45.00	17.29	34.82	30.27	45.00	15.15	34.23
Annual Net Benefits (Billion Rs)	106.56	110.90	102.03	106.47	106.03	110.59	124.03	129.37
First 100 Years								
Groundwater Extractions (Bm^3)	3.68	3.67	3.32	3.67	3.67	3.67	3.69	3.73
Water Table Height (m)	21.48	45.00	8.11	27.64	27.14	45.00	5.26	27.10
Annual Net Benefits (Billion Rs)	105.03	110.90	99.66	104.28	105.01	110.59	121.20	126.89
Discounted Total Net Benefits at Steady State (Billion Rs)	2165.79	2218.03	1070.38	1085.50	1088.98	1105.88	1299.49	1317.71
Welfare Gains from Optimal Management (Percent)	2.41		1.41		1.55		1.40	

Note: OA = Open Access; OM = Optimal Management; SA3 (Sensitivity Analysis 3): discount rate (d) = 0.05; SA4 (Sensitivity Analysis 4): surface water supplies (q_{sw}) = 10.13 Bm^3; SA5 (Sensitivity Analysis 5): marginal extraction cost per unit of lift (γ) = 0.086 Rs m^{-3} m^{-1}; SA6 (Sensitivity Analysis 6): water demand function intercept (a_0) = 21.07 Rs.

Figures



Groundwater Extractions (Open Access)

Watertable Height (Open Access)

Annual Net Benefits (Open Access)

Figure 1: Dynamics of extractions, aquifer state, and net benefits under open access

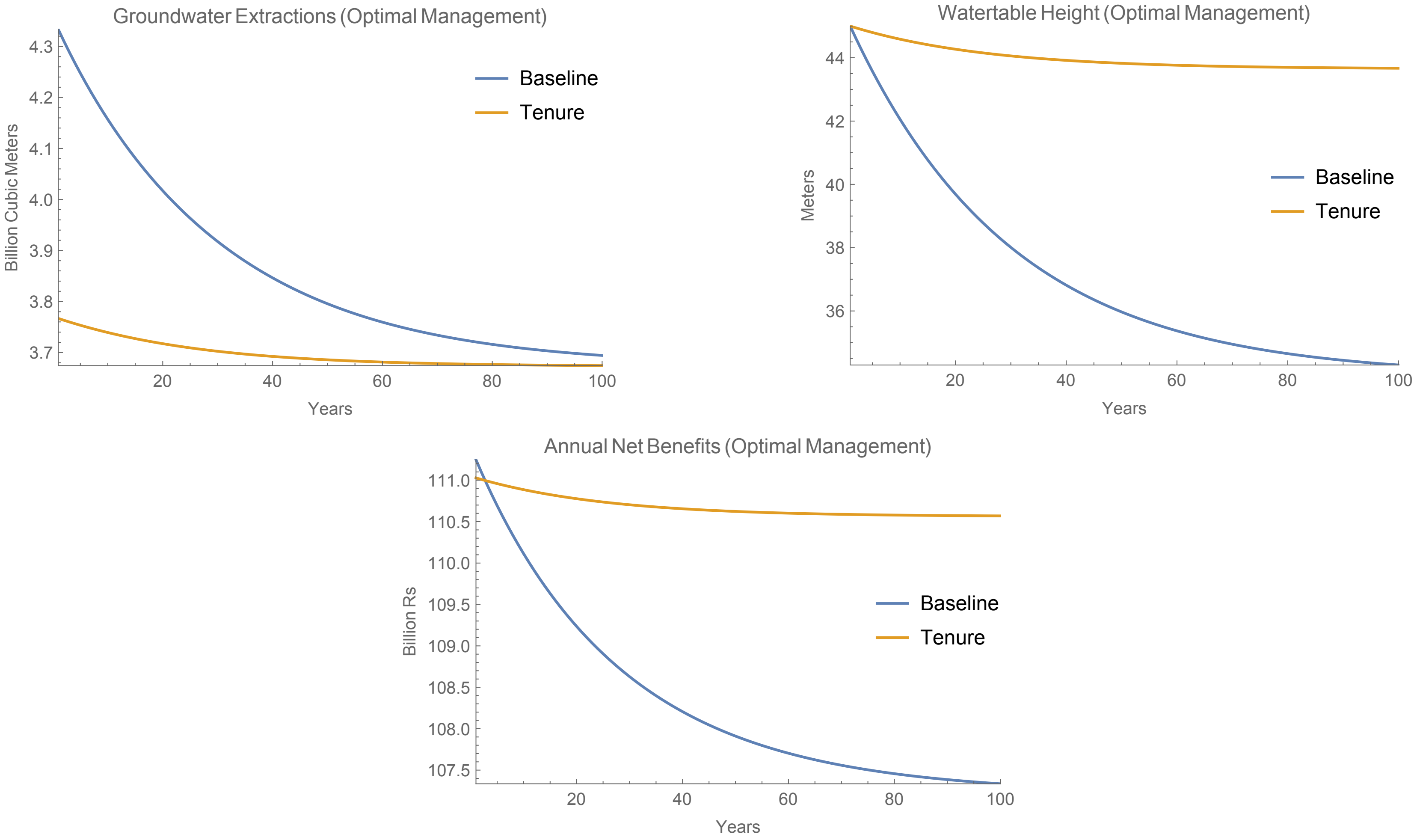


Figure 2: Dynamics of extractions, aquifer state, and net benefits under optimal management

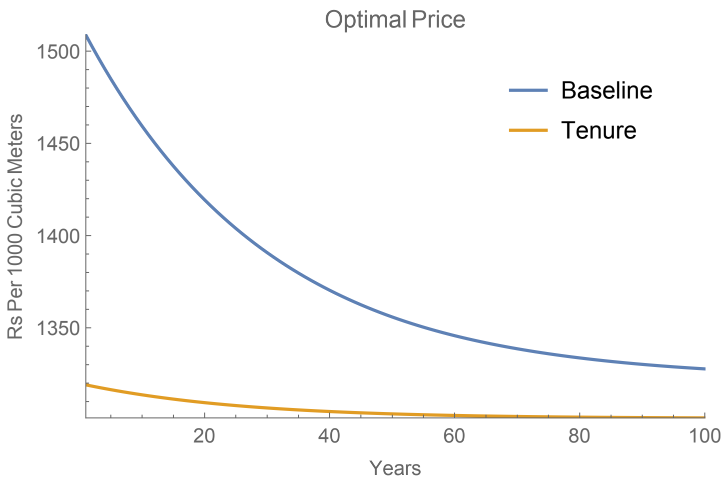


Figure 3: Optimal groundwater extraction price