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Optimal Groundwater Management in Pakistan's Indus Water Basin

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INTRODUCTION

Water for irrigation is a major concern in agricultural production in many countries around the world. Pakistan is home to one of the largest and most complex irrigation infrastructure systems in the world, consisting of 25 million hectares of irrigated agriculture, 56,000 kilometers of main canals, tubewells in excess of 600,000, and with nearly 100 million people depending on 107,000 water courses fed by 44 canal systems (Hussain 2004; Briscoe and Qamar 2006). Ineffective water-management policies in the past have affected water availability, water quality, and soil quality. This is likely to have generated adverse effects for agriculture and the livelihoods of the rural poor who depend on the sector.

The core water management issues for irrigation in Pakistan include: low water charges for users, limited water storage capacity, inequitable distribution of water entitlements between head-end and tail-end users, and over-exploitation of groundwater. The current political economy and institutional arrangement have led to inefficient and unsustainable use of water in the agricultural sector. The Government of Pakistan Planning Commission's *Vision 2025* strategy lists water security as a major priority for Pakistan's long-term development and stresses the urgent need to conserve irrigation water.

Since the 1960s groundwater has become an important source of irrigation in Pakistan's Indus Water Basin. Initially, groundwater use yielded significant economic and environmental benefits (Briscoe and Qamar 2006). However, the largely unmanaged extraction of groundwater has led to continuous depletion of the resource and has reduced its accessibility (Qureshi et al. 2009). Since groundwater quality is related to the depth of the aquifer, depletion of groundwater has also reduced the quality of the available groundwater in certain parts of the Indus Basin.

Evidence from the Indus Basin shows that farms irrigated with only groundwater or groundwater in conjunction with surface water have 50-100 percent higher crop yields compared to farms irrigated with only surface water (Shah 2007). The reduction in the availability of groundwater and the deterioration of groundwater quality will have an adverse impact on land productivity and on farm profits in the future. Policy interventions are needed to control the unsustainable use of groundwater in Pakistan.

As a result of the ineffective water management policies, farmers have created informal institutions to cope with the declining and highly variable supply of irrigation water. The official *warabandi* system provides turns (based on time) for the water supply entering the watercourse, which farmers unofficially exchange or rotate (Bandaragoda and Rehman, 1995). The collective-action literature suggests that local (and informal) institutions can provide a mechanism for farmers to cooperate and efficiently manage irrigation water (Ostrom 1990; 2007). However, these institutions can also fail to allocate irrigation water efficiently if knowledge and trust gaps exist amongst farmers (Ostrom, 2011).

Moreover, institutional constraints affect the degree of utilization of groundwater in Pakistan's agricultural sector. Tenure arrangements are one form of institutional constraint in Pakistan that affects farmers' decision to optimally extract groundwater. Agricultural tenure falls under three basic categories: owner-cultivation, fixed-rent tenancy, and sharecropping. According to the Government of Pakistan Statistics Division (2012), owner-cultivators operate approximately two thirds of total cultivable land. Since Pakistan's independence in 1947, state and market-assisted land reform as well as other economic forces have led to a decline in sharecropping and a rise in owner-cultivation (Cheema and Nasir, 2010). The incentives for efficient utilization of resources under each form of tenure differ, and consequently production and input-use decisions vary across tenure as well. Differences in incentives across tenure arrangements may explain a portion of Pakistan's groundwater-management issues (Dinar et al. 2004).

To ensure the future sustainability of Pakistan's agricultural sector, the unrestricted extraction of groundwater and the continuous decline of the water table in the Indus Water Basin are issues that need to be addressed through improved groundwater management. Designing policies for optimal management[1] of groundwater in Pakistan's Indus Water Basin requires a comprehensive groundwater extraction model with simultaneous considerations of surface water recharge, groundwater extraction, groundwater quality, and water table height. A dynamic groundwater extraction model that simulates the long-run trends of the water table height and groundwater quality, and their impact on farm profits, could help policymakers to formulate appropriate groundwater-conservation policies.

[1] We use the terms optimal management and optimal control interchangeably throughout the report.

In this report we examine the management of groundwater in Pakistan's Indus Basin through a model of groundwater extraction with hydrologic, economic, and tenure constraints. We develop a groundwater extraction model for the Indus Basin and simulate the effect of common property management (the status quo in the Indus Basin) and optimal management on groundwater extractions, water table height, groundwater quality, and annual net benefits from irrigated agriculture. The analysis provides a framework to develop and discuss policies that could lead to the optimal management of groundwater.

We acknowledge that the model developed here is not an operational model of the Indus Water Basin since it does not include the heterogeneous nature of the Indus Basin and is not calibrated to explain the spatial variation in aquifer characteristics. In certain regions of the Indus Basin, especially southern Punjab, excessive canal water seepage can lead to waterlogging, which might remain unaffected by groundwater extractions in other regions. The model developed in this paper captures average effects of groundwater extractions. The model emphasizes long run dynamics and permits us to examine the impact of various economic and hydrological parameters on aquifer recharge, groundwater pumping, water table height, groundwater quality, and net benefits across the Indus Basin. Sensitivity analysis can be used to understand the variation in the aquifer characteristics observed across space.

This study builds on our previous work under the Pakistan Strategy Support Program, which analyzed the allocative inefficiency of groundwater in Punjab and Sindh provinces.[2] In previous research we focused only on Punjab and Sindh since the bulk of groundwater irrigation occurs in these two provinces. We estimated the degree of over and under-utilization of groundwater and discussed policies that could improve the allocative efficiency of groundwater in Punjab and Sindh.[3]

In this study we examine the long-run trends of groundwater depletion in Pakistan's Indus Water Basin under common-pool resource management—the status quo—and under optimal management. We develop a dynamic optimization problem to illustrate long-run steady states of groundwater pumping under different management, hydrologic, economic, and tenure assumptions. Whereas the focus of the previous study was on farm-level utilization and allocation of groundwater in Pakistan, this study emphasizes the sustainability of the aquifer of the Indus Water Basin under different groundwater management schemes. We also provide an analysis of a set of policies that can lead to the optimal level of groundwater extractions and limit the overdraft of the aquifer underlying the Indus Basin. The analysis helps to inform the larger discussion on the effective governance of water resources in the region.

The next section provides a review of the literature on the optimal management of groundwater. In Section 3 we model groundwater extractions under various hydrological, economic, management and tenure assumptions. We examine the results of the models in Section 4. In Section 5 we describe various policies that could lead to optimal groundwater extractions and more effective management of groundwater resources. Section 6 concludes the report.

BRIEF LITERATURE REVIEW

The following literature review first explores the theoretical and empirical research on dynamic groundwater management, and then briefly addresses relevant work on tenure arrangements.

Groundwater Management

Resource economists argue that in the absence of intervention groundwater will be misallocated under certain management conditions. When groundwater withdrawals exceed the recharge of water into the aquifer, the pumping of groundwater will continue over time until the resource is completely diminished or until the marginal cost of extracting groundwater exceeds the marginal benefit of using an additional unit of groundwater. The reduction in groundwater for future use reflects the marginal user cost of the resource: the present value of forgone future net benefits owing to a unit of extraction of groundwater in the present.

Under common property resource management, farmers fail to account for the marginal user cost of pumping groundwater in the present. An optimal allocation of groundwater considers the marginal user cost of pumping groundwater and reflects the scarcity value (or scarcity rent) of the resource. Under optimal groundwater management

[2] Pakistan consists of four provinces (Punjab, Sindh, Khyber Pakhtunkhwa, and Balochistan), a federal capital territory (Islamabad Capital Territory), two autonomous territories with de facto province-like status (Azad Kashmir and Gilgit-Baltistan), and several federally administered tribal areas.

[3] See Nasim et al. (2014).

the pricing of groundwater includes both the marginal extraction cost of groundwater and the marginal user cost of groundwater. Such a pricing scheme imposes the scarcity rent of the resource on groundwater users.

Gisser and Sanchez (1980) were the first to compare the evolution of groundwater extractions and the water table height under common property management with the case under optimal control. Using data from the Pecos Basin in New Mexico, they showed that social benefits from optimal control were insignificant. This result is known as the Gisser-Sanchez effect and has inspired a vast literature on groundwater management.

Gisser and Sanchez (1980) considered a simple hydrological-economic model to analyze the pumping choices of groundwater users. The benefit function for groundwater users is given by:

$$\pi(t) = V[w(t)] - C[H(t)]w(t) \tag{1}$$

Where $\pi(t)$ are the profits at time t. The net farm revenue from groundwater use $w(t)$—the control variable—is given by $V(w) = \int_0^w p(x)dx$, where $p(x)$ is the inverse demand function for groundwater. $C(H)$ is the marginal extraction cost of groundwater and $H(t)$—the state variable—is the height of the water table at time t.

The change in the height of the water table over time is given by the differential equation:

$$\dot{H} = \frac{1}{AS}[R + (a-1)w], \quad H(0) = H_0 \tag{2}$$

Where R is the constant recharge of groundwater, a is the constant return flow coefficient (the percentage of groundwater applied to the field that seeps back into the aquifer), H_0 is the initial level of the water table, A is the surface area of the aquifer, and S is the specific yield of the aquifer (the amount of water per unit volume that would drain from an aquifer under the influence of gravity). The differential equation (2) reflects the hydrologic state of the aquifer.

The aquifer in the model above is considered an "unconfined" aquifer with infinite hydraulic conductivity (the aquifer never completely drains). The model assumes a constant return flow, which implies a constant rate of groundwater application when the groundwater pumping technology is fixed. The model also assumes a constant recharge rate, which suggests that land use remains constant over time and ignores linkages between surface water and groundwater hydrologic systems. Capital costs and replacement costs are not included in the model and energy costs are assumed to be constant over time.[4]

Using the hydrological-economic model described above, Gisser and Sanchez examined the evolution of groundwater application and the height of the water table over time in the Pecos Basin in New Mexico. They first conducted the analysis under the assumption of common property management and then under the assumption of optimal control. Under the assumption of common property, management decision variables are chosen to maximize annual net benefits in each year given the current values of the state variables. Under the assumption of optimal control, users maximize the present value of net benefits over multiple time periods.

Their results for the evolution of groundwater pumping and the height of the water table were almost identical under both forms of management. Their figures for the present value of the net profits over time were also very close, leading them to conclude that welfare gains from optimal control were negligible—the literature refers to this as the Gisser-Sanchez effect. Given the simplistic assumptions about the aquifer in the Gisser Sanchez model the results explained above might be misleading. The benefits from optimal control might be promising under more realistic assumptions regarding the aquifer and farmer behavior.

Relevant works on groundwater management since Gisser and Sanchez (1980) include the following:

Feinerman and Knapp (1983) used data from Kern County in California to estimate benefits of optimal groundwater control and found evidence to support the Gisser-Sanchez effect. In contrast, Worthington et al. (1985)

[4] Our model relies on most of the assumptions listed here. However, we allow for linkages between surface water and groundwater hydrologic systems by including surface water recharge of the aquifer through canal water seepage and deep percolation.

simulated a model with nonlinear marginal extraction costs of water and found large differences in benefits under optimal control and competition. They also showed that benefits from optimal control were significant when considering heterogeneity in land productivity.

Koundouri and Christou (2000) used data from the Kiti aquifer in Cyprus to show that in the absence of a backstop technology and with an aquifer near depletion, optimal control increased welfare by more than 400 percent. Brozovic et al. (2010) modeled the spatial nature of the groundwater pumping externality and demonstrated significant benefits of optimal control for large unconfined aquifers. Esteban and Dinar (2012) developed an optimal control model for the Western la Mancha aquifer in Spain and included the impact of groundwater extractions on groundwater-dependent ecosystems. They showed that optimal control is necessary to ensure the well being of ecosystems if they have a large monetary value.

Roseta-Palma (2002) examined the dynamics of both groundwater quantity and quality under common property management and under optimal control. She showed that optimal control would lead to an improvement in one of the variables at the expense of the other. Knapp and Baerenklau (2006) developed a groundwater model with aquifer salinization as an additional externality. They used data from Kern County to simulate the evolution of both quantity and quality of groundwater and found that optimal control led to higher groundwater table levels and lower salt concentrations.

From the review of the studies above we conclude the following: first, the Gisser-Sanchez effect does not hold with more realistic assumptions regarding the economic and hydrologic variables. Second, the benefits of optimal control depend on the initial state of the specific aquifer being examined. Given the gradual depletion of the groundwater aquifers in Pakistan—a water-scarce country with a vibrant agricultural sector—the possible benefits from optimal groundwater management over common pool resource management (the status quo) is a topic that requires further analysis. We address this topic in this report by adapting the Gisser-Sanchez model to include differences in tenure and more realistic linkages between surface water and groundwater hydrologic systems.

Tenure Arrangements

The Marshallian inefficiency associated with sharecropping—the idea that output sharing between a tenant and a landlord acts as a tax on the tenant's effort inducing him to reduce output and input below the competitive level—has been extensively debated in the literature. The institutional literature (Stiglitz, 1974; Braverman and Stiglitz, 1986; Agrawal, 2002) shows that while sharecropping can be efficient in a local sense—landlords and tenants cannot make a Pareto improvement through another tenure contract—it can also lead to inefficient input use and lower land productivity.

On the empirical side, evidence of the Marshallian inefficiency has been mixed. Shaban (1987) showed that a sample of farmers in India who cultivated their own plots and plots leased-in under a sharecropping agreement had significantly lower output intensity and input intensity on the sharecropped plots. Similarly, Jacoby and Mansuri (2009) find that unsupervised share tenants in Pakistan have lower yields on their sharecropped plots compared to yields on plots that they own and cultivate. However, they do not find any significant differences in yields across owner cultivated plots and sharecropped plots that are supervised.

Jacoby and Mansuri (2008) find that non-contractible investment is underprovided on sharecropped plots in Pakistan, suggesting the presence of the perverse effects of moral hazard in sharecropping. Feder and Feeny (1991) and Feder et al. (1998) use data from Thailand to demonstrate that allocating lands rights to tenanted farmers can significantly increase input intensity and land productivity. Nasim et al. (2014) and Nasim (2015) use a panel dataset from Pakistan to show that sharecroppers use groundwater less intensely than owner cultivators, though both groups over-utilize the resource. Nabi (1986), on the other hand, finds that sharecroppers from a small sample of farmers in Pakistan are allocatively efficient, owing to optimal sharing agreements with their landlords.

The brief review of the sharecropping literature suggests that there is substantial—though not unanimous—evidence of the Marshallian inefficiency in sharecropping, which could lead to observable differences in groundwater extractions compared to owner cultivators. We will model this inefficiency associated with sharecropping and explore its implications for long run groundwater quantity and quality. The sharecropping literature also shows that the production decisions of owner cultivators and fixed-rent tenants are identical—there is no Marshallian inefficiency in fixed-rent tenancy. Therefore, we exclude fixed-rent tenancy from the analysis. To our knowledge, this is the first study to examine the optimal control of groundwater in the Indus Basin and to include the effect of tenure on groundwater extraction decisions.

METHODOLOGY

In this section we describe the hydrological-economic model of groundwater extraction for the Indus Basin. We then explain the decision rules for deriving solutions under common property management and under optimal control. At the end of the section we describe the data used and the calibration of the model.

Hydrological-Economic Model of Groundwater Extraction

We follow Gisser and Sanchez (1980) and Esteban and Albiac (2011) to formulate a hydrological-economic model for the Indus Water Basin. The dynamic model that we develop links hydrological and economic variables of groundwater usage. We calibrate the model using data from Punjab since the majority of groundwater extractions (90 percent) in the Indus Water Basin occur in Punjab.[5] We begin by defining the water demand, marginal cost, and net benefit functions and then connect these with the characteristics of the aquifer. 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 groundwater extractions, 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 in Punjab. The inverse water demand function is given by:

$$P(Q_t) = a_0 - a_1 Q_t \qquad (3)$$

Where:

$P(Q_t)$ is the marginal willingness to pay for irrigation water (surface water and groundwater) in Rs per cubic meter in time period t.

Q_t is the quantity of irrigation water: $Q_t = (1-\beta_{SW})Q_{SW_t} + Q_{GW_t}$ in billion cubic meters (Bm^3):

Q_{SW} is the total quantity of surface water available in the canal commands for agricultural use in Punjab.

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.

Q_{GW} is the total quantity of groundwater extracted in Punjab.

a_0 is the intercept of the water demand function.

a_1 is the slope of the water demand function.

The area under the water demand function gives the annual total revenue from irrigated agriculture:

$$R(Q_t) = \int_0^{(1-\beta_{SW})Q_{SW_t}+Q_{GW_t}} P(Q_t)\,.\,dQ_t \qquad (4)$$

Following the literature (Esteban and Albiac, 2011; Knapp and Baerenklau, 2006; Laukkanen and Koundouri, 2006) we assume the marginal cost of extraction of groundwater to be constant and a function of the depth from which groundwater has to be extracted:

$$MEC\left(Q_{GW_t}\right) = \gamma(H_L - H_t) \qquad (5)$$

[5] See Qureshi et al. (2003).

Where:

$MEC(Q_{GW_t})$ is the marginal extraction cost of groundwater in Rs per cubic meter in time period t.

γ is the marginal cost of extraction of groundwater per unit of lift in Rs per cubic meter per meter—it shows the marginal cost of extracting a cubic meter of groundwater from a depth of 1 meter.

H_L is the surface elevation in meters.

H_t is the water table height in meters.

The difference between the surface elevation and the water table height $(H_L - H_t)$ is the depth from which groundwater has to be extracted. The function $\gamma(H_L - H_t)$ therefore shows the marginal cost of extraction of a cubic meter of groundwater from a depth of $(H_L - H_t)$ meters.

The annual total cost of groundwater extractions is given by:

$$C\left(Q_{GW_t}\right) = \int_0^{Q_{GW_t}} MEC(Q_{GW_t})\,.\,dQ_{GW_t} \qquad (6)$$

A constant marginal extraction function implies that the total cost of pumping groundwater 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).

We assume that groundwater salt concentration c_{gw_t} in each period has a linear impact on annual net benefits. The groundwater salt concentration is the total salt mass K_t dissolved in the groundwater divided by the total volume of groundwater (AS_yH_t), where A is the area of the aquifer and S_y is the specific yield of the aquifer, which is a fraction that measures the storage capacity of the aquifer. Groundwater salt concentration is given by:

$$c_{gw_t} = \frac{K_t}{AS_yH_t} \qquad (7)$$

We further assume uniform mixing of the total salt mass in the aquifer—the groundwater salt concentration is homogenous in the entire aquifer. The linear impact of the groundwater salt concentration implies that as the groundwater salt concentration c_{gw_t} increases by a unit the annual net benefits fall by δ percent.

The annual net benefit function (annual total revenue minus annual total cost) from irrigated agriculture is given by:

$$\pi_t = \left(\int_0^{(1-\beta_{SW})Q_{SW_t}+Q_{GW_t}} P(Q_t)\cdot dQ_t - \int_0^{Q_{GW_t}} MEC\left(Q_{GW_t}\right)\cdot dQ_{GW_t}\right)\ \left(1-\delta c_{gw_t}\right) \qquad (8)$$

$$\pi_t = \left(\int_0^{(1-\beta_{SW})Q_{SW_t}+Q_{GW_t}} (a_0 - a_1Q_t)\cdot dQ_t - \int_0^{Q_{GW_t}} \gamma(H_L - H_t)\cdot dQ_{GW_t}\right)\ \left(1-\delta\left(\frac{K_t}{AS_yH_t}\right)\right) \qquad (9)$$

$$\pi_t = \left(a_0\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right) - \frac{a_1}{2}\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right)^2 - \gamma(H_L - H_t)Q_{GW_t}\right)\left(1-\delta\left(\frac{K_t}{AS_yH_t}\right)\right) \qquad (10)$$

The annual net benefit π_t is a function of the control variable Q_{GW_t} (quantity of groundwater extracted) and the state variables H_t (height of the water table) and K_t (total salt mass in the groundwater).

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. We adapt the model by Gisser and Sanchez (1980) and Esteban and Albiac (2011) to include surface water recharge characteristics in the equation of motion of the water table height. Knapp and Baerenklau (2006) use a similar adaptation. The water table height evolves over time according to the following equation of motion:

$$H_{t+1} = H_t + \frac{\beta_{SW} Q_{SW_t} + \beta_{DP}\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right) + \omega - Q_{GW_t}}{AS_y} \qquad (11)$$

Where: β_{SW} is the percentage of surface water that seeps into the aquifer during delivery from the canal level to the field level; 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 being applied to the crops on the field; and ω is the recharge of groundwater from rainfall.

The equation of motion of the water table height shows that over time the seepage from canal water delivery, deep percolation from irrigation, and the recharge from rainfall cause the water table to rise while groundwater extractions cause the water table to fall. The water table height and ground water extractions are in steady state (or equilibrium) when:

$$H_{t+1} - H_t = \frac{\beta_{SW} Q_{SW_t} + \beta_{DP}\left((1-\beta_{SW})Q_{SW_t} + Q_{GW}^{SS}\right) + \omega - Q_{GW}^{SS}}{AS_y} = 0 \qquad (12)$$

When ground water extractions are greater than Q_{GW}^{SS} the total groundwater extractions exceed the total recharge of the aquifer and the water table height falls in the next period. If the extractions are less than Q_{GW}^{SS} then the total recharge exceeds the total groundwater extractions and the water table level rises in the next period.

Modifying the groundwater quality specification in Knapp and Baerenklau (2006), we use the following equation of motion of groundwater quality:

$$K_{t+1} = K_t + c_{sw} Q_{SW_t} + c_\omega \omega \qquad (13)$$

Where c_{sw} represents surface water salt concentration and c_ω denotes salt concentration from rainfall. The equation shows that groundwater salt mass does not reach a steady state since the salt mass in the aquifer keeps building up over time as a result of continuous seepage of saline surface water and saline rainfall. We convert the total salt mass into a concentration using equation (7) and report the dynamics of this concentration in the results section below.

Decision Rules

Under the common property regime (the status quo in Punjab) the effect of groundwater extractions in the present period on the state of the aquifer in the future is neglected. Under this regime profits are maximized in each period without regard for the future values of the state variables. Therefore, under the common property management scheme decision variables are chosen to maximize annual net benefits in each year given the current values of the state variables. The maximization problem can be stated as:

$$Max_{Q_{GW_t}} \sum_{t=0}^{\infty} \left[\left(a_0\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right) - \frac{a_1}{2}\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right)^2 - \gamma(H_L - H_t)Q_{GW_t} \right) \left(1 - \delta\left(\frac{K_t}{AS_y H_t}\right)\right)\right]$$

Subject to the constraints:

$$Q_{GW_t} \geq 0$$

$$H_{t+1} = H_t + \frac{\beta_{SW} Q_{SW_t} + \beta_{DP}\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right) + \omega - Q_{GW_t}}{AS_y}$$

$$K_{t+1} = K_t + c_{sw}Q_{SW_t} + c_\omega \omega$$

$$0 \le H_t \le 375$$

$$H_0 = 370$$

$$0 \le c_{gw} < 4.0$$

$$c_{gw_0} = 2.0$$

The boundary constraint $0 \le H_t \le 375$ states that the water table height has to be positive and cannot exceed 375 m. Since the surface elevation is 380 m we are constraining the maximum water table height to be 5 meters less than the surface elevation. If this constraint is relaxed the water table height could potentially lead to water logging. The constraint keeps the water table height within an acceptable limit.

The constraint $0 \le c_{gw} < 4.0$ keeps the groundwater salt concentrations within a limit that can be tolerated by crops. Groundwater salt concentrations in excess of 4.0 dSm^{-1} are considered hazardous for crop production. The constraint ensures that groundwater salt concentrations do not exceed this value.

Under optimal management a social planner maximizes the present value of net benefits over multiple time periods subject to the boundary constraints and the equation of motion of the water table height specified earlier. The problem is solved using dynamic programming in which the value function (optimized objective function) is given by:

$$V(H_0, K_0) = Max_{Q_{GW_t}} \sum_{t=0}^{\infty} \alpha^t \left[\left(a_0\big((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\big) - \frac{a_1}{2}\big((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\big)^2 - \gamma(H_L - H_t)Q_{GW_t} \right) \left(1 - \delta\left(\frac{K_t}{AS_y H_t}\right)\right)\right]$$

Subject to the constraints:

$$Q_{GW_t} \ge 0$$

$$H_{t+1} = H_t + \frac{\beta_{SW}Q_{SW_t} + \beta_{DP}\big((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\big) + \omega - Q_{GW_t}}{AS_y}$$

$$K_{t+1} = K_t + c_{sw}Q_{SW_t} + c_\omega \omega$$

$$0 \le H_t \le 375$$

$$H_0 = 370$$

$$0 \le c_{gw} < 4.0$$

$$c_{gw_0} = 2.0$$

Where H_0, K_0 and c_{gw_0} are the initial (base period) values of the state variables. The value function V must satisfy Bellman's equation of the form:

$$V(H, K) = Max_{Q_{GW}} \big[\pi(H, K, Q_{GW}) + \alpha V[g(H, K, Q_{GW})]\big] \qquad (14)$$

Where π is the annual net benefits defined implicitly in terms of the water table height, the groundwater salt mass, and groundwater extractions and g is a vector function that gives the water table height and the groundwater salt mass in the next period as functions of the state variables and groundwater extractions. The vector function g is defined by the equations of motion of the water table height (equation 12) and the groundwater salt mass (equation 13).

The dynamic programming problem consists of solving the Bellman equation (14) for the unknown value function V and optimal extractions as functions of the state variables. We use an iterative procedure consistent with the dynamic programming literature (Judd, 1998) to approximate the value function and solve for the optimal extraction path.

Under common property management the groundwater extractions (the control variable) each year depend on the current height of the water table (the first state variable) and the current concentration of groundwater salinity (the second state variable). The groundwater extractions under optimal management depend not only on the current height of the water table and the current concentration of groundwater salinity but also on the discounted value of the impact of current extractions on future net benefits.

Data Sources

Table 1 below shows the values of the parameters used to simulate the baseline model. We use the agricultural year 2009-2010 as the base year (initial period) of the model. All rupee values taken from other sources were converted to 2009 values using the Consumer Price Index.

Table 1: Model Parameters

Parameter	Description	Value
a_0	Intercept of the water demand function	18.91 Rs
a_1	Slope of the water demand function	0.19 Rs/Bm^3
γ	Marginal cost of extraction of groundwater per unit of lift	0.04 $Rs/m^3 \cdot m$
β_{SW}	Coefficient of surface water seepage into the aquifer	0.30
δ	Percentage reduction in net benefits per unit increase in groundwater salt concentration	0.125
β_{DP}	Deep percolation	0.30
ω	Recharge from rainfall	3.00 Bm^3
A	Area of the aquifer	99.64 Bm^2
S_y	Specific yield	0.14
c_{sw}	Surface water salt concentration	0.2 dSm^{-1}
c_ω	Rainfall salt concentration	0.1 dSm^{-1}
H_L	Surface Elevation	380 m
H_0	Initial water table height	370 m
c_{gw_0}	Initial groundwater salt concentration	2.0 dSm^{-1}
α	Discount factor	0.99

We have calibrated the values of the intercept (a_0) and the slope (a_1) of the water demand function using data from the *Punjab Development Statistics* (2012), *Pakistan Agricultural Statistics* (2010), and Nasim (2013). The calibration process is described in the subsection that follows.

The value of the marginal cost of extraction of groundwater per unit of lift (γ) is taken from Qureshi et al. (2009). The values of the coefficient of surface water seepage into the aquifer (β_{SW}), deep percolation of irrigation water (β_{DP}), and rainfall recharge (ω) are taken from Hussain et al. (2011). We have used values of the specific yield (S_y) and the average surface elevation (H_L) from a study by the US Geological Survey conducted in Pakistan.[6] The average initial water table height (H_0) in the base year is calculated from data in Basharat et al. (2014) and the value of the area of the aquifer (A) is taken from the same source.

The values of the surface water salt concentration and the rainfall salt concentration are taken from Kijne (1996). The value of the linear impact of the groundwater salt concentration on net benefits (δ) is an average value calculated from Kijne (2003). We have used the value of the initial groundwater salt concentration from Qureshi at al. (2009).

The discount factor (α) is given by $\frac{1}{1+r}$ where r is the real interest rate. We used data for the period 2004-2013 from *International Financial Statistics* provided by the International Monetary Fund to calculate an average value of 0.6 percent for the real interest rate in Pakistan. The data shows that in Pakistan the real interest rate has historically been low—even negative in some years—owing to high rates of inflation.

Calibration of the Water Demand Function

Nasim (2013) uses data from the *Pakistan Agricultural Census* (2010) to calculate the net value of output from irrigated agriculture in Punjab in the agricultural year 2009-2010, which is approximately Rs 704 billion. Data from the *Punjab Development Statistics* (2012) and the *Pakistan Agricultural Statistics* (2010) shows that in the agricultural year 2009-2010 total canal withdrawals in Punjab were 62.6 Bm^3 while total groundwater extracted in Punjab was 55.7 Bm^3.

Using $\pi_0 =$ Rs 704 billion, $Q_{SW_0} = 62.6\ Bm^3$, $Q_{GW_0} = 55.7\ Bm^3$, $\beta_{SW} = 0.30$, $\gamma = 0.04\ Rs/m^3 \cdot m$, $H_L = 380\ m$, $H_0 = 370\ m$, $\delta = 0.125$, $c_{gw_0} = 2.0\ dSm^{-1}$ and substituting these values into equation (10)—the expression for the annual net benefit from irrigated agriculture in Punjab—we get:

$$\left(a_0(99.52) - \frac{a_1}{2}(99.52)^2 - 22.28\right)(0.75) = 704 \quad (15)$$

The first order condition for profit maximization implies:

$$P(Q_t) = MEC\left(Q_{GW_t}\right) \quad (16)$$

$$a_0 - a_1\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right) = \gamma(H_L - H_t) \quad (17)$$

Using the values above for Q_{SW_0}, Q_{GW_0}, β_{SW}, γ, H_L and H_0 and substituting these into equation (17) we get:

$$a_0 - a_1(99.52) = 0.4 \quad (18)$$

After solving equation (15) and equation (18) we get:

$$a_0 = 18.91\ Rs$$

$$a_1 = 0.19\ Rs/Bm^3$$

We use the calibrated water demand function along with the cost and hydrological parameters described earlier to conduct our analysis and derive the long run trend of the water table height, the groundwater salt concentration, groundwater extractions, and the annual net benefits under common property management and under optimal control.

[6] See Bennet et al. (1967).

Inclusion of Tenure

We follow the institutional economics literature on sharecropping (Stiglitz, 1974; Braverman and Stiglitz, 1986; Agrawal, 2002) to include behavioral differences between owner cultivators and sharecroppers in the baseline model and simulate long run dynamics of the physical and economic variables. We assume that sharecroppers and owner cultivators have an identical production function and a portion of owner cultivators lease out their land to sharecroppers—this implies that owner cultivators are the sharecroppers' landlords. We also assume that production is risky and that sharecroppers are risk averse, while owner cultivators who lease out their land to sharecroppers are risk neutral. From equation (3) we know that the water demand function can be written as:

$$Q(P_t) = \frac{a_0}{a_1} - \frac{P_t}{a_1} \tag{19}$$

Using the superscripts OC and SC to denote owner cultivators and sharecroppers respectively, we disaggregate the water demand function given by equation (19) into separate water demand functions for owner cultivators and sharecroppers:

$$Q^{OC}(P_t) = \delta^{OC}\left(\frac{a_0}{a_1} - \frac{P_t}{a_1}\right) \tag{20}$$

$$Q^{SC}(P_t) = \delta^{SC}\left(\frac{a_0}{a_1} - \frac{P_t}{a_1}\right) \tag{21}$$

Where δ^{OC} is the total share of owner cultivators and δ^{SC} is the total share of sharecroppers.

From equations (20) and (21) the inverse water demand functions for owner cultivators and sharecroppers are given by:

$$P^{OC}(Q_t) = a_0 - \frac{a_1}{\delta^{OC}}\,Q_t \tag{22}$$

$$P^{SC}(Q_t) = a_0 - \frac{a_1}{\delta^{SC}}\,Q_t \tag{23}$$

Given the total amount of surface water withdrawals each year ($\bar{Q}_{SW_t}$), the amount of surface water available to owner cultivators and sharecroppers is given by:

$$Q^{OC}_{SW_t} = \delta^{OC}\bar{Q}_{SW_t} \tag{24}$$

$$Q^{SC}_{SW_t} = \delta^{SC}\bar{Q}_{SW_t} \tag{25}$$

The net benefits from irrigated agriculture for owner cultivators and sharecroppers are given by:

$$\pi^{OC}_t = \left(\int_0^{(1-\beta_{SW})Q^{OC}_{SW_t}+Q^{OC}_{GW_t}} P^{OC}(Q_t).\,dQ_t - \int_0^{Q^{OC}_{GW_t}} MEC(Q_{GW_t}).\,dQ_{GW_t} + (f)\int_0^{(1-\beta_{SW})Q^{SC}_{SW_t}+Q^{SC}_{GW_t}} P^{SC}(Q_t).\,dQ_t \right.$$
$$\left. - (v)\int_0^{Q^{SC}_{GW_t}} MEC(Q_{GW_t}).\,dQ_{GW_t}\right)\left(1 - \delta\left(\frac{K_t}{AS_yH_t}\right)\right) \tag{26}$$

$$\pi^{SC}_t = \left((1-f)\int_0^{(1-\beta_{SW})Q^{SC}_{SW_t}+Q^{SC}_{GW_t}} P^{SC}(Q_t).\,dQ_t - (1-v)\int_0^{Q^{SC}_{GW_t}} MEC(Q_{GW_t}).\,dQ_{GW_t}\right)\left(1 - \delta\left(\frac{K_t}{AS_yH_t}\right)\right) \tag{27}$$

Where f and v are the landlords' share of the output and groundwater cost respectively. Equation (26) shows that the net benefit of owner cultivators comprises the profit from the owner cultivators' own production and the owner cultivators' share of the sharecroppers' revenue net of the owner cultivators' share of the cost of groundwater. The net benefit of sharecroppers in equation (27) includes the sharecroppers' share of their profit minus his share of the cost of groundwater.

Under common property management in a given period, owner cultivators maximize π_t^{OC} and sharecroppers maximize π_t^{SC} subject to the constraints described earlier. The first order condition of profit maximization for owner cultivators is given by:

$$P^{OC}(Q_t) = MEC\left(Q_{GW_t}\right) \tag{28}$$

Using the functional forms for the water demand function and the marginal extraction cost of groundwater, the first order condition of profit maximization implies:

$$a_0 - \frac{a_1}{\delta^{OC}} Q_t = \gamma(H_L - H_t) \tag{29}$$

Since $Q_t = (1-\beta_{SW})Q_{SW_t} + Q_{GW_t}$, the optimal level of groundwater extractions for owner cultivators is:

$$Q_{GW_t}^{OC^*} = \frac{\delta^{OC}\left(a_0 - \gamma(H_L - H_t)\right) - a_1(1-\beta_{SW})Q_{SW_t}^{OC}}{a_1} \tag{30}$$

The first order condition of profit maximization for sharecroppers is given by:

$$(1-f)P^{SC}(Q_t) = (1-v)MEC\left(Q_{GW_t}\right) \tag{31}$$

Using the functional forms for the water demand function and the marginal cost of extraction, we solve for the optimal level of groundwater extractions for sharecroppers:

$$Q_{GW_t}^{SC^*} = \frac{\delta^{SC}\left((1-f)a_0 - (1-v)\gamma(H_L - H_t)\right) - a_1(1-f)(1-\beta_{SW})Q_{SW_t}^{SC}}{a_1(1-f)} \tag{32}$$

If $f > v$ then the optimal level of groundwater applied by sharecroppers would be less than the optimal level of groundwater applied by owner cultivators. The optimal levels of groundwater applied by owner cultivators and by sharecroppers would be equal when $f = v$. If monitoring costs are negligible, the landlord can also set $f > v$ and enforce the optimal level of input intensity.

Under the institutional economics literature (Stiglitz, 1974; Braverman and Stiglitz, 1986), if production is risky and sharecroppers lack access to insurance markets, a risk neutral landlord would set $f > 0$ to absorb some of the sharecropper's risk. However, there is a tradeoff since $f > 0$ would also decrease the sharecropper's input intensity vis-à-vis Marshallian inefficiency—output sharing acts as a tax on the tenants effort. Therefore, there exists an optimal level of output and input cost shares that insures sharecroppers against risk and maximizes the rent extracted from the sharecropper by the landlord. The landlord can minimize the Marshallian inefficiency by monitoring and enforcing the effort of the sharecropper.

In the model we assume that monitoring costs are high, sharecroppers lack access to insurance markets and production is risky. We further assume that under a sharecropping contract landlords set $f > v$. These assumptions are necessary in order to impose Marshallian inefficiency of sharecropping in the model and see discernable differences in the input intensity of sharecroppers and owner cultivators.

CALIBRATION

In the tenure 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 have to recalibrate the water demand function to account for difference in the optimization behavior of sharecroppers. We use the base year (2009-2010) values from the previous calibration to calibrate the tenure model.

Using the optimality conditions given in equations (30) and (32), the optimal extractions $(Q_{GW_t}^{OC^*} + Q_{GW_t}^{SC^*})$ in the base period are:

$$Q_{GW_0}^{*} = \frac{\delta^{OC}\left(a_0 - \gamma(H_L - H_0)\right) - a_1(1-\beta_{SW})Q_{SW_0}^{OC}}{a_1} + \frac{\delta^{SC}\left((1-f)a_0 - (1-v)\gamma(H_L - H_0)\right) - a_1(1-f)(1-\beta_{SW})Q_{SW_0}^{SC}}{a_1(1-f)} \quad (33)$$

Where $\delta^{OC} = 0.9$ and $\delta^{SC} = 0.1$—values of the total shares of owner cultivators and sharecroppers are taken from the *Pakistan Agricultural Census* (2010). We use $f = 0.5$ and $v = 0$ as the values of the shares of the landlords' output and groundwater cost, which are observed as common values in the data (Pakistan Rural Household Survey I and II) and are sufficient to induce Marshallian inefficiency in the optimization behavior of sharecroppers.

The annual net benefits $(\pi_t^{OC} + \pi_t^{SC})$ in the base period are:

$$\pi_0 = \left(\int_0^{(1-\beta_{SW})Q_{SW_0}^{OC} + Q_{GW_0}^{OC}} \left(a_0 - \frac{a_1}{\delta_t^{OC}} Q_0\right).dQ_0 - \int_0^{Q_{GW_0}^{OC}} \gamma(H_L - H_0).dQ_{GW_0} + (f)\int_0^{(1-\beta_{SW})Q_{SW_0}^{SC} + Q_{GW_0}^{SC}} \left(a_0 - \frac{a_1}{\delta_t^{SC}} Q_0\right).dQ_0 - (v)\int_0^{Q_{GW_0}^{SC}} \gamma(H_L - H_0).dQ_{GW_0}\right)\left(1 - \delta\left(\frac{K_0}{AS_y H_0}\right)\right) + \left((1-f)\int_0^{(1-\beta_{SW})Q_{SW_0}^{SC} + Q_{GW_0}^{SC}} \left(a_0 - \frac{a_1}{\delta_t^{SC}} Q_0\right).dQ_0 - (1-v)\int_0^{Q_{GW_0}^{SC}} \gamma(H_L - H_0).dQ_{GW_0}\right)\left(1 - \delta\left(\frac{K_0}{AS_y H_0}\right)\right) \quad (34)$$

Using values of the various parameters and variables from the previous calibration we solve the system of equations given by equations (33) and (34) for a_0 and a_1 (parameters of the water demand function), which gives:

$$a_0 = 18.87\ Rs$$

$$a_1 = 0.19\ Rs/Bm^3$$

The annual net benefits π_t is a function of the control variables $Q_{GW_t}^{OC}$ (quantity of groundwater extracted by owner cultivators) and $Q_{GW_t}^{SC}$ (quantity of groundwater extracted by sharecroppers) and the state variables H_t (height of the water table) and K_t (total salt mass in the groundwater).

The evolution of the state variables is given by:

$$H_{t+1} = H_t + \frac{\beta_{SW}\left(Q_{SW_t}^{OC} + Q_{SW_t}^{SC}\right) + \beta_{DP}\left((1-\beta_{SW})\left(Q_{SW_t}^{OC} + Q_{SW_t}^{SC}\right) + \left(Q_{GW_t}^{OC} + Q_{GW_t}^{SC}\right)\right) + \omega - \left(Q_{GW_t}^{OC} + Q_{GW_t}^{SC}\right)}{AS_y} \quad (35)$$

$$K_{t+1} = K_t + c_{sw}\left(Q_{SW_t}^{OC} + Q_{SW_t}^{SC}\right) + c_{\omega}\omega \quad (36)$$

The model described above is solved using the same decision rules regarding common property management and optimal management described earlier. As in the baseline model, for the tenure model we present results for the long run dynamics of the water table height, the groundwater salt concentration, groundwater extractions and the annual net benefits.

RESULTS

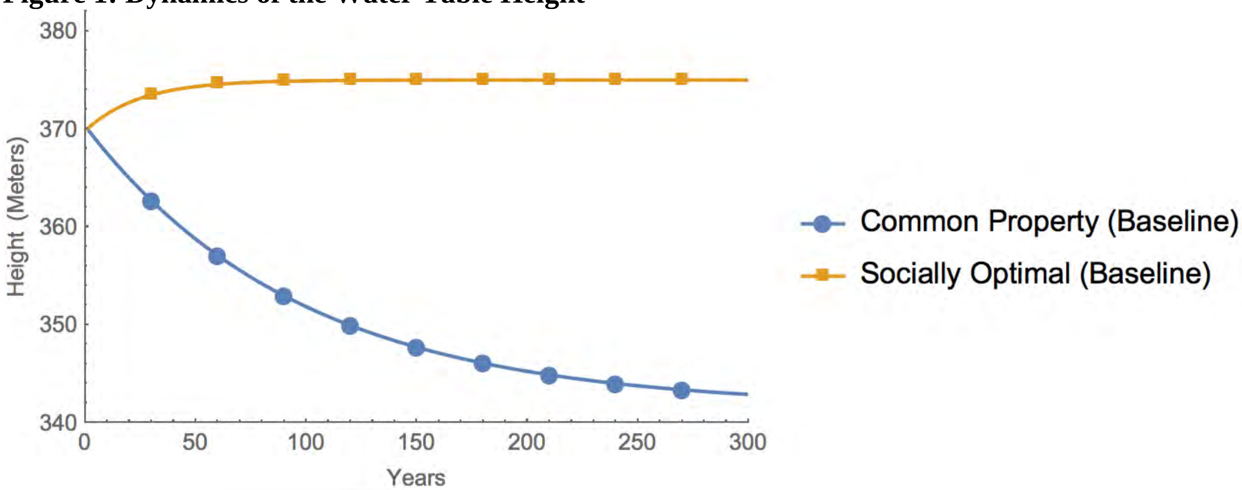
In this section we first present the results of the baseline model. We then describe the various sensitivity analyses that we conducted and present their results. In the final subsection we present the results of the tenure model. Table 2 at the end of the section summarizes all the key results discussed below.

The results have been simulated with a time horizon of 300 years. For large aquifers, the time horizon for water table height and groundwater salt concentrations to achieve steady state can be significantly long (Knapp and Baerenklau, 2006). Nonetheless, the results allow for a comparison of the state of the aquifer under common property management and under optimal control for shorter periods (the first 50 years), which is likely a more appropriate time horizon for devising policies for groundwater sustainability.

Baseline Results

Figure 1 and Table 2 show the dynamics of the water table height under the common property regime and under optimal management.[7] Under the common property regime the water table height falls steadily and reaches a level of 342 meters after 300 years. In the first 50 years, the water table height falls by 12 meters.

Figure 1: Dynamics of the Water Table Height



Under optimal management the water table height rises over time and reaches a steady state at the boundary constraint of 375 meters after about 100 years. The groundwater extractions under optimal control are initially less than the steady state level and hence the water table height rises over time.

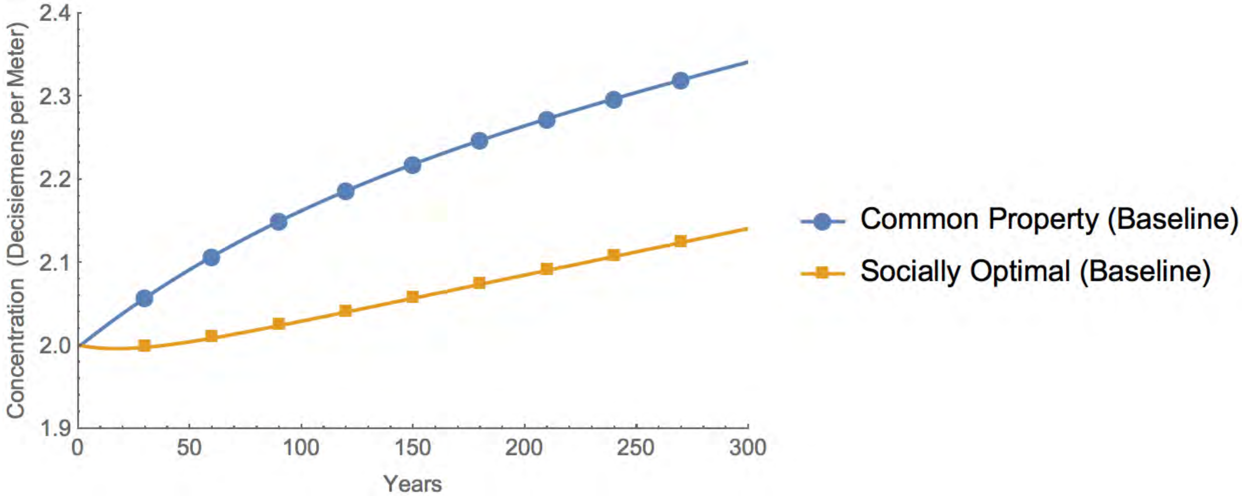
The dynamics of the groundwater salt concentration are shown in Figure 2 below. Under the common property management regime the groundwater salt concentration increases steadily over time from an initial average concentration level of 2.0 dSm^{-1}. The groundwater salt concentration increases as the water table height falls, which leads to a reduction in the volume of groundwater in the aquifer. The total salt mass keeps increasing in the aquifer owing to constant seepage of saline surface water and rainfall in the aquifer—salts in the soil dissolve in rainwater and leach into the aquifer. As the total salt mass rises and the volume of groundwater falls, the groundwater salt concentration increases. In the first 50 years the groundwater salt concentration under the common property regime increases by 0.9 dSm^{-1}. This increase in groundwater salt concentration translates into a 1.25 percent reduction in net benefits, which decline as the quality of groundwater deteriorates.

Under optimal management the groundwater salt concentration falls initially as the water table height rises and the volume of groundwater in the aquifer increases. However, after the first 25 years the increase in total salt mass dominates the increase in the volume of groundwater so that the groundwater salt concentration starts to increase. The concentration is around 2.0 dSm^{-1}—the same as the concentration in the initial period—after the first 50 years.

[7] We refer to the results presented in this section as the baseline results. The results of the sensitivity analyses and the tenure simulations presented in the subsections that follow are compared with the baseline results.

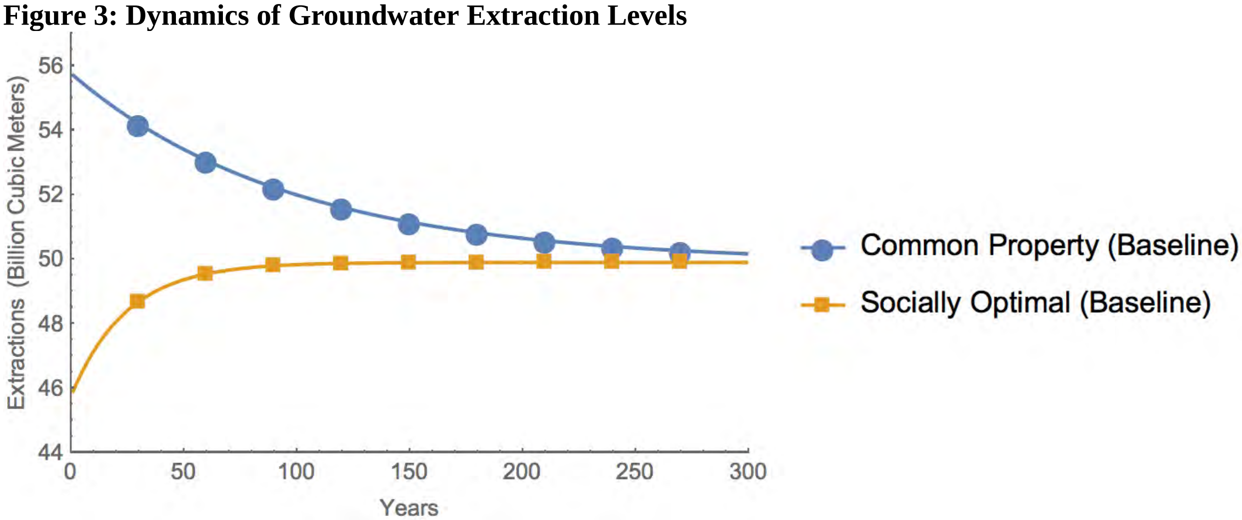
In every period, the groundwater salt concentration is lower under optimal management than under the common property regime, and this difference increases over time.

Figure 2: Dynamics of the Groundwater Salt Concentration



The long term trend of groundwater extractions are shown in Figure 3 below. Since the water table falls over time under the common property regime, the groundwater extractions are initially greater than the recharge. As the water table height falls, the marginal cost of extraction increases and groundwater extractions fall over time and reach a steady state of 49.9 Bm^3 after around 300 years. About 50 percent of the adjustment towards the steady state takes place in the first 50 years.

Figure 3: Dynamics of Groundwater Extraction Levels

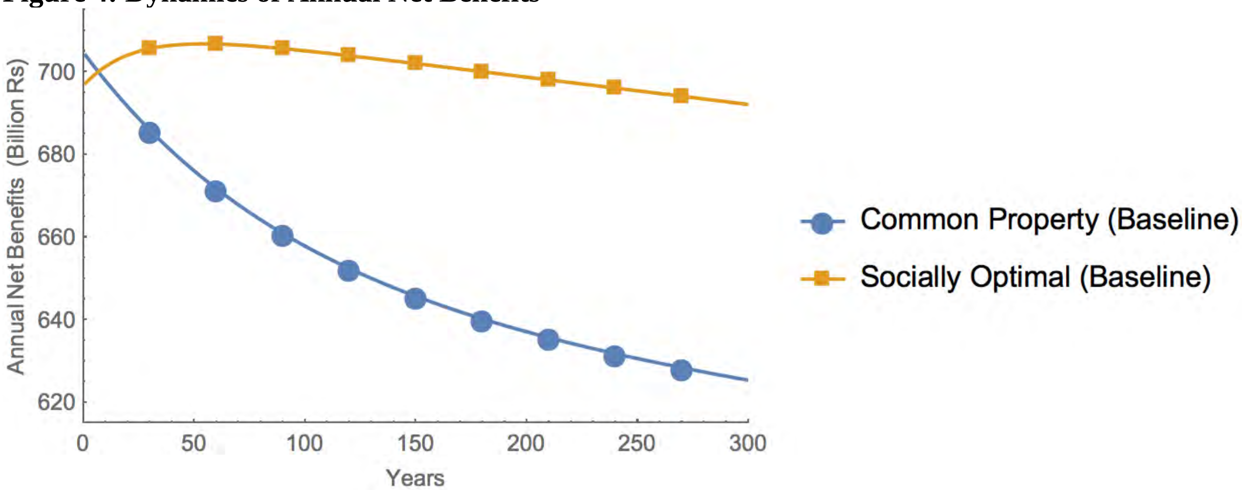


Under optimal management the water table height increases over time since the recharge exceeds the level of extractions. The marginal cost of extraction falls over time and groundwater extractions increase. The extractions reach the steady state after about 100 years. About 95 percent of the adjustment towards the steady state occurs in the first 50 years.

The marginal cost of groundwater extractions under optimal control internalizes the discounted value of the forgone net benefits from pumping groundwater in the present (marginal user cost). Given the high value of the discount factor (99 percent), the marginal user cost of groundwater extractions is also high enough to push initial extractions below the steady state level. Moreover, under optimal management a lower level of initial extractions is a form of investment for farmers. Since under optimal management the extraction decision depends on the current and the future values of the state variables, a lower initial level of extractions implies higher net benefits in the future owing to a higher water table level and better quality groundwater.

Figure 4 below shows the dynamics of the annual net benefits under both forms of management. The net benefits fall over time under the common property regime since the water table height falls and the groundwater salt concentration increases. Under optimal management the annual net benefits increase initially as the water table height increases and the groundwater salt concentration falls. After about 25 years, the increase in the annual net benefits starts tapering off as the groundwater salt concentrations start to increase even though the water table height rises gradually towards the steady state. After about 100 years when the water table height and groundwater extractions reach a steady state, the groundwater salt concentration rises at a slow pace and the net benefits start to fall. However, at this stage the net benefits from optimal management exceed the net benefits under the common property regime by Rs 40 billion and this difference keeps increasing over time.

Figure 4: Dynamics of Annual Net Benefits



Sensitivity Analyses

We now examine the sensitivity of the results to changes in the values of the parameters of the model. We conduct five different sensitivity analyses. In the first two sensitivity analyses we change the values of the hydrological parameter β_{DP} and the quantity of surface water Q_{SW}. The value of the parameter β_{DP} in the baseline model is an average value and could possibly be lower in certain parts of Punjab. In sensitivity analysis 1 we use a lower value of β_{DP} (0.20). Spatial differences in the value of β_{DP} can lead to heterogeneous differences in the recharge of the aquifer. A lower value of this parameter would lead to less recharge of the aquifer and a quicker drawdown of groundwater.

Moreover, in our model we treat surface water supply as a fixed factor. The supply of surface water is variable and could also potentially fall over time as a result of climate change and other factors. Sensitivity analysis 2 looks at the case when surface water supply is reduced by 25 percent. In sensitivity analysis 3 we increase the salt concentration of surface water from 0.2 dSm^{-1} to 0.3 dSm^{-1}. Since the seepage of saline surface water into the aquifer increases the total salt mass in the aquifer, sensitivity analysis 3 allows us to examine the impact of a higher flow of salt mass into the aquifer on the salt concentration of groundwater.

In the last two sensitivity analyses we examine different values of the parameters of the marginal cost and the water demand functions. In sensitivity analysis 4 we lower the marginal extraction cost of groundwater to half the marginal extraction cost in the baseline model. This could reflect technological change that lowers extraction costs. We use this case as a lower bound for the variation in the results due to a decrease in the cost of extraction.

Similarly, we examine the impact on the water table height, groundwater extractions, and annual net benefits due to an increase in total benefits (revenue). Price subsidies for crops or more intensive cultivation can shift the water demand function outwards and increase net benefits. In sensitivity analysis 5 we decrease the slope of the water demand equation in the baseline model by 10 percent—this change leads to an approximately 10 percent increase in total benefits. The relevant parameter values under each sensitivity analysis are given below:

Sensitivity Analysis 1:

$\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient)

Sensitivity Analysis 2:

$Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water)

Sensitivity Analysis 3:

$c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water)

Sensitivity Analysis 4:

$\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction)

Sensitivity Analysis 5:

$a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope)

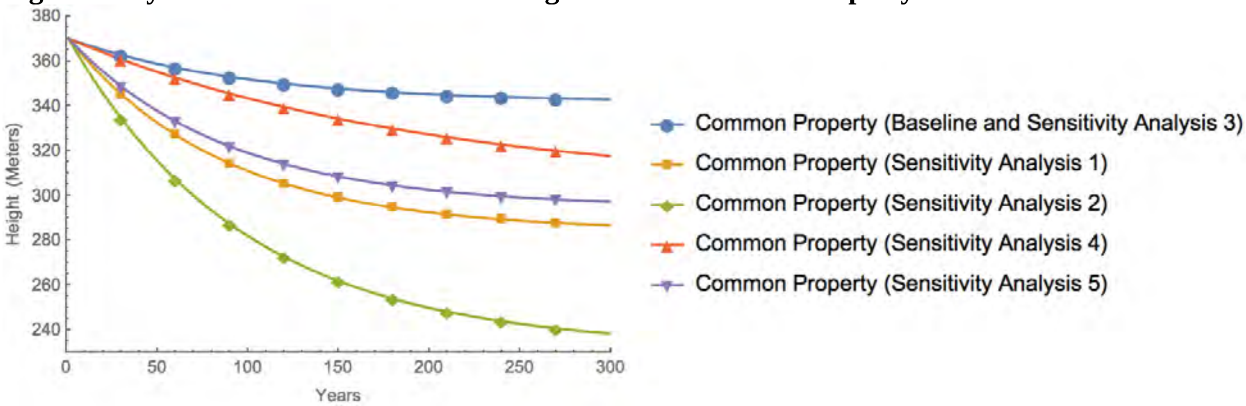
RESULTS OF THE SENSITIVITY ANALYSES

Figures 5 and 6 and Table 2 show the dynamics of the water table height under common property management and under optimal control. Under common property management, the water table height under all five sensitivity analyses falls more rapidly compared to the baseline model. Reduction in the surface water supply (sensitivity analysis 2) has the largest impact on the water table height compared to the baseline model and all the other sensitivity analyses, since the recharge of the aquifer in this case is the lowest. In sensitivity analysis 2 the water table height falls by 50 meters in the first 50 years. The decrease from 0.3 to 0.2 in the deep percolation parameter β_{DP} (sensitivity analysis 1) also has a significant impact on the water table height. After the first 50 years the water table height falls by 40 meters.

In the first 50 years, the fall in the water table height under sensitivity analysis 4 (half the marginal extraction cost) is smaller compared to the fall in the water table height under sensitivity analyses 5 (10 percent decrease in the water demand slope). Under sensitivity analysis 5 the initial net benefits from groundwater extractions are larger than the initial net benefits under sensitivity analyses 4, which leads to greater extractions under sensitivity analysis 5. Therefore, the water table height falls more rapidly under sensitivity analysis 5 compared to sensitivity analysis 4 and reaches a steady state at a lower level.

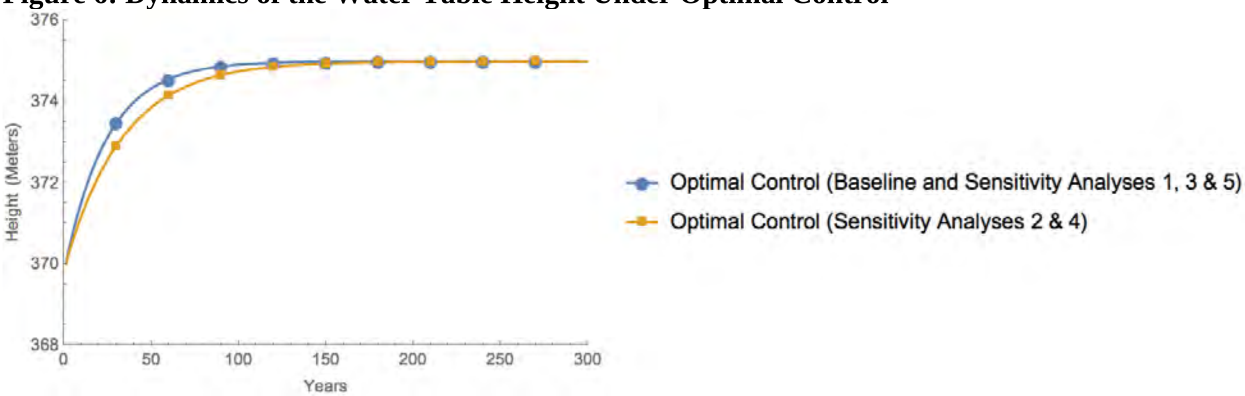
The fall in the water table height under sensitivity analysis 3 (50 percent increase in the salt concentration of surface water) is the same as the fall in the water table height under the baseline model. Since the equation of motion of groundwater quality is independent of groundwater extractions, the increase in the surface water salt concentration affects the salinity of the aquifer but not groundwater extractions. Hence, the water table height under the baseline model is unaffected by the increase in the surface water salt concentration.

Figure 5: Dynamics of the Water Table Height Under Common Property



Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water); Sensitivity Analysis 4: $\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction); Sensitivity Analysis 5: $a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope under the baseline model).

Figure 6: Dynamics of the Water Table Height Under Optimal Control



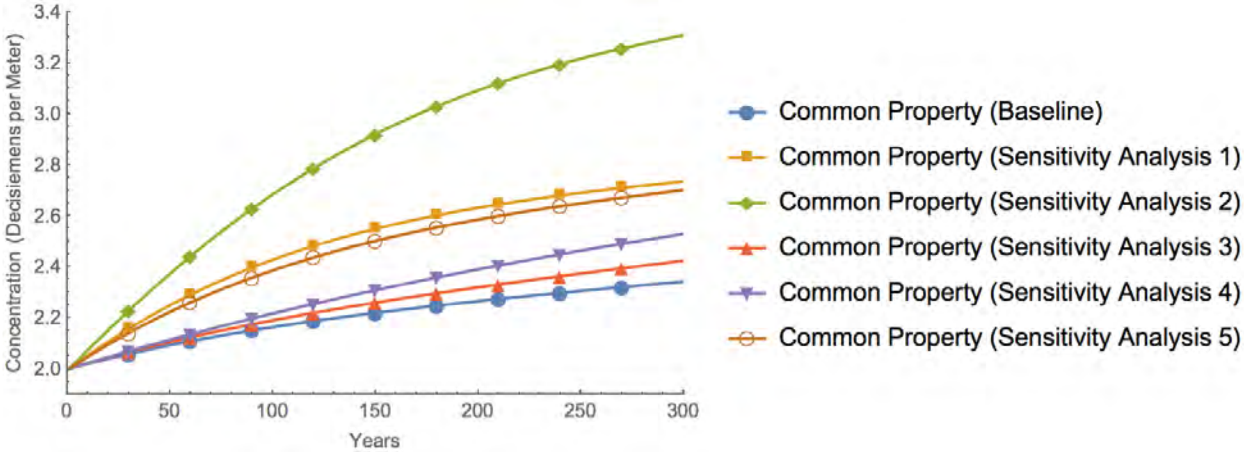
Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water); Sensitivity Analysis 4: $\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction); Sensitivity Analysis 5: $a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope under the baseline model).

The optimal management control steady state solutions under all sensitivity analyses are almost identical. Under optimal control, the water table level rises until it reaches the boundary condition of 375 meters. In sensitivity analyses 2 and 4 the rate of increase of the water table height is marginally slower compared to all the other sensitivity analyses—although the difference is negligible. Given the high discount factor, the marginal user cost of extraction is high enough in all the cases to drive extractions below the steady state level. Therefore, the groundwater recharge each year dominates extractions, and the water table height increases over time until the steady state is achieved.

The dynamics of the groundwater salt concentration under the common property regime and under optimal management are shown in Figures 7 and 8 below. Under all the sensitivity analyses, the groundwater salt concentration increases slowly over time, since the fall in the water table height decreases the volume of groundwater in the aquifer while the seepage of saline surface water and rainfall increases the salt mass in the aquifer. The groundwater salt concentration under sensitivity analyses 3 and 4 is close to the concentration under the baseline model after the first 50 years—about 2.1 dSm^{-1}.

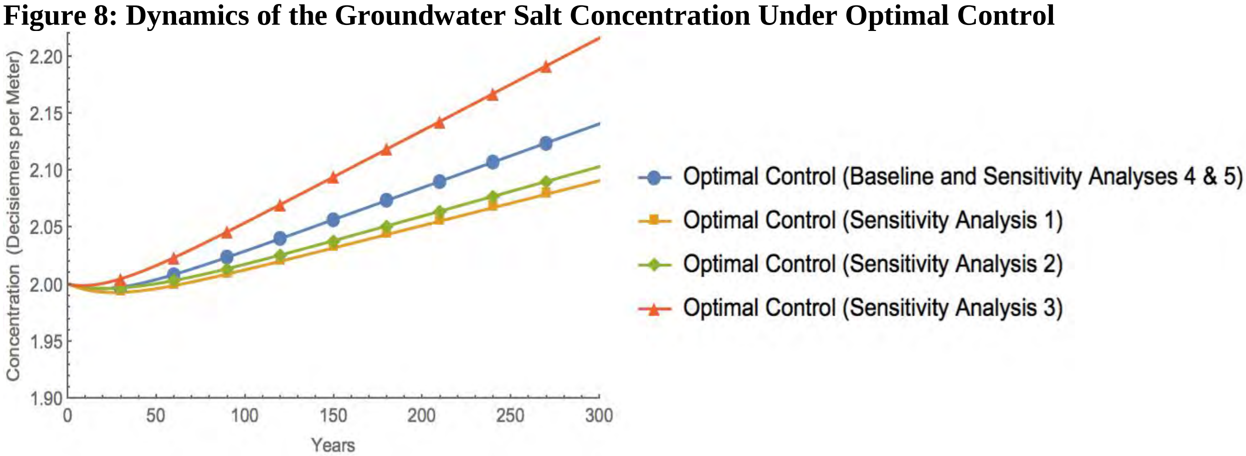
The groundwater salt concentration under sensitivity analyses 2 is greater than the concentration under all the other sensitivity analyses because the reduction in the volume of groundwater under sensitivity analysis 2 is the largest. The groundwater salt concentration under sensitivity analyses 2 is at 2.4 dSm^{-1} after the first 50 years. Under sensitivity analyses 1 and 5, the groundwater salt concentration is similar and at a level of 2.2 dSm^{-1} after the first 50 years.

Figure 7: Dynamics of the Groundwater Salt Concentration Under Common Property



Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water); Sensitivity Analysis 4: $\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction); Sensitivity Analysis 5: $a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope under the baseline model).

Figure 8: Dynamics of the Groundwater Salt Concentration Under Optimal Control



Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water); Sensitivity Analysis 4: $\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction); Sensitivity Analysis 5: $a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope under the baseline model).

Under optimal control, the groundwater salt concentration falls initially (first 25 years) in all the sensitivity analyses. This occurs as the water table height rises and the volume of groundwater in the aquifer increases more in proportion to the increase in the salt mass. After the first 25 years, the increase in the water table height becomes more gradual and the increase in the salt mass dominates the increase in the volume of groundwater in the aquifer. The groundwater salt concentration starts increasing as a result.

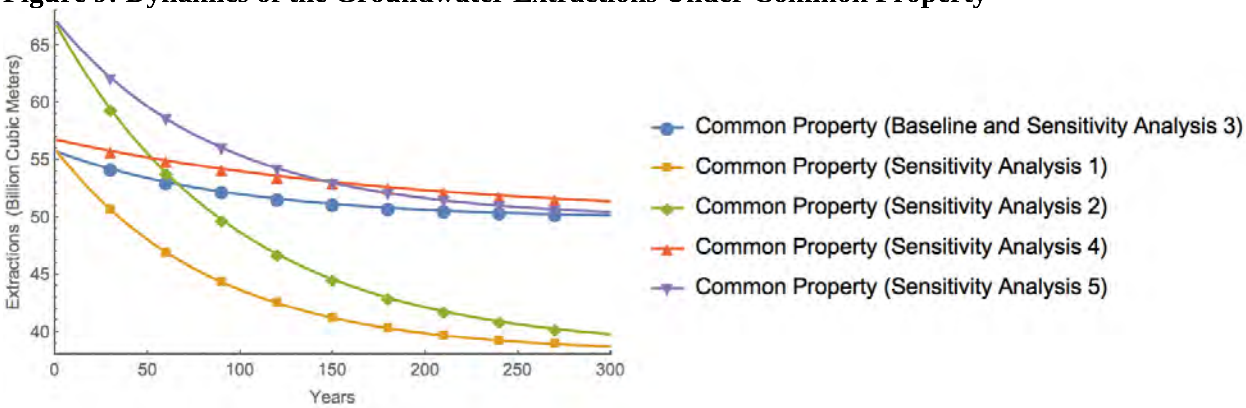
The groundwater salt concentration is the highest under sensitivity analysis 3 and lowest under sensitivity analysis 1 in each year. However, the concentration levels after the first 50 years are between 2.0-2.02 dSm^{-1} under all the sensitivity analyses. For each of the sensitivity analysis, the groundwater salt concentration under optimal control is well below the concentration under the common property regime.

The corresponding dynamics of groundwater extractions are shown in Figures 9 and 10 below. Since the steady state level of extractions neither depends on the parameters of the marginal cost function nor the parameters of the water demand function, the extractions in sensitivity analyses 4 and 5 converge to the same level as in the baseline model (49.9 Bm^3). The extractions under sensitivity analysis 3 (50 percent increase in the salt concentration of surface water) are the same as under the baseline model since extractions under the common property decision rule are dependent on the current height of the water table and not the current level of the groundwater salt concentration.

Under common property management, the initial extractions in sensitivity analyses 2, 4, and 5 are greater than the initial extractions in the baseline model, since the initial net benefits under these three sensitivity analyses are greater than the net benefits under the baseline model. Extractions in sensitivity analyses 1 and 3 converge to the same steady state level (38.2 Bm^3).

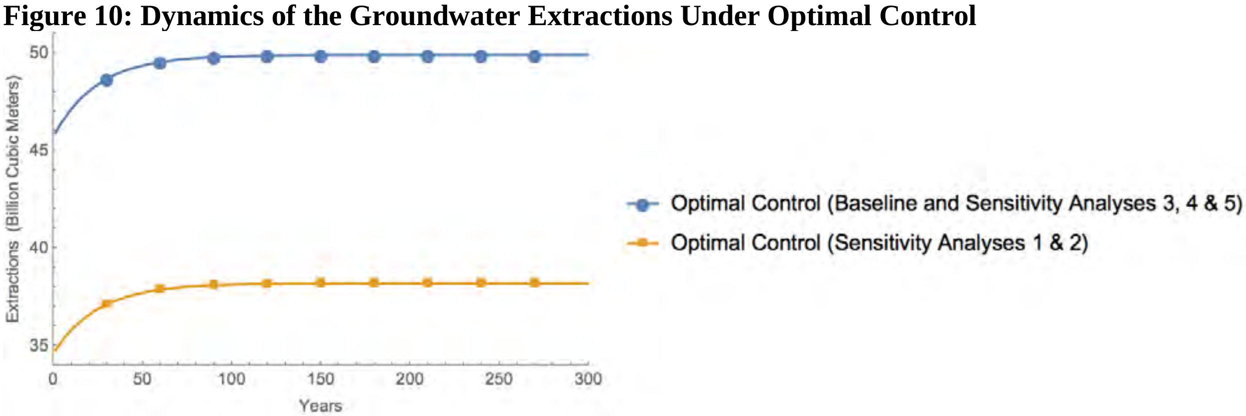
Moreover, in all five sensitivity analyses the initial levels of extractions under optimal management are below the steady state levels. Since extractions depend on the current and future values of the state variables, the lower level of initial extractions implies a higher water table level and better groundwater quality in the future. In all of these cases the recharge effect dominates the extractions, and the water table height rises in the subsequent period until it reaches a steady state.

Figure 9: Dynamics of the Groundwater Extractions Under Common Property



Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water); Sensitivity Analysis 4: $\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction); Sensitivity Analysis 5: $a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope under the baseline model).

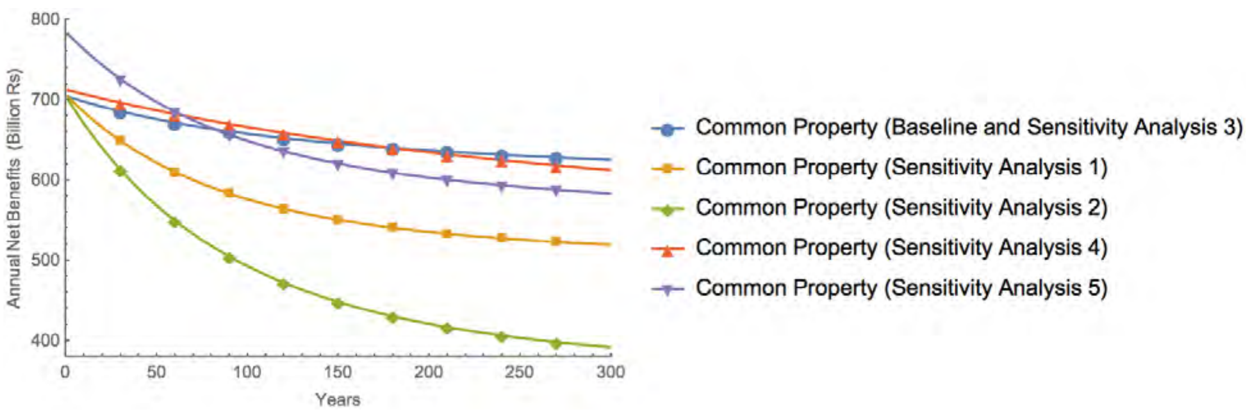
Figure 10: Dynamics of the Groundwater Extractions Under Optimal Control



Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water); Sensitivity Analysis 4: $\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction); Sensitivity Analysis 5: $a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope under the baseline model).

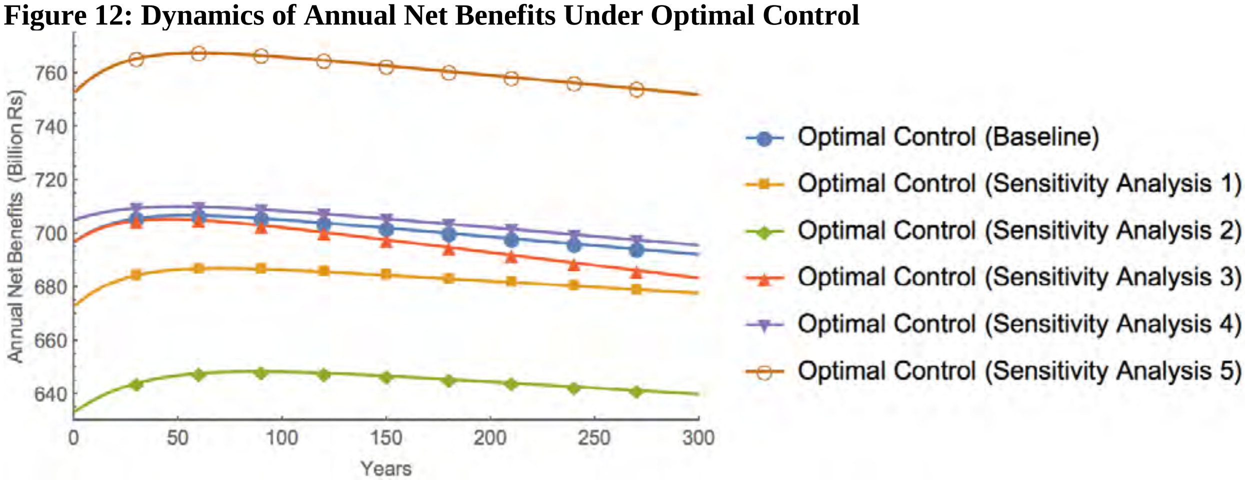
Figures 11 and 12 below show the dynamics of the annual net benefits under each form of management. Under common property management, in the first 50 years the net benefits given by sensitivity analyses 1 and 2 are less than the net benefits under the baseline model, while the net benefits given by sensitivity analyses 4 and 5 are greater than the net benefits under the baseline model. The annual net benefits given by sensitivity analysis 3 are approximately the same as the annual net benefits given by the baseline model.[8] The fall in net benefits is quickest over time when the quantity of surface water is lower (sensitivity analysis 2) since the fall in the water table height and the increase in the groundwater salt concentration in this case is the most pronounced. In all the common property management cases (including the baseline) the range of the net benefits in the first 50 years is Rs 560 - 720 billion.

Figure 11: Dynamics of Annual Net Benefits Under Common Property



Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water); Sensitivity Analysis 4: $\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction); Sensitivity Analysis 5: $a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope under the baseline model).

Figure 12: Dynamics of Annual Net Benefits Under Optimal Control



Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water); Sensitivity Analysis 4: $\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction); Sensitivity Analysis 5: $a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope under the baseline model).

The results also show that the net benefits from optimal control over time are much larger than the net benefits under common property management. In all the optimal cases (including the baseline model) the net benefits after the first 50 years are in the range between Rs 650 billion and Rs 770 billion. In all the optimal control cases the water table height increases over time and the total cost of extraction falls as a result. Moreover, in the first 25 years the groundwater salt concentration falls slightly, which has a positive impact on net benefits. After this period, the groundwater salt concentration starts to increase gradually, and net benefits fall by 12.5 percent for every unit increase in concentration.

[8] Under common property management the annual net benefits given by sensitivity analysis 3 are slightly less than the annual net benefits given by the baseline model since the impact of salinity on net benefits is higher in sensitivity analysis 3. However, the difference is too small to distinguish between the two in Figure 11.

The sensitivity analyses described above provide valuable insight into the dynamics of the aquifer, groundwater extractions, and net benefits for exogenous changes in the hydrological and economic parameters of the baseline model. Changes in the hydrological parameters are important in terms of spatial differences in recharge that might be observed in the Indus basin. The deep percolation of applied irrigation water in certain geographic areas might be different from the average value of 0.30 that we have used in our baseline model. Simulating changes in the deep percolation coefficient (sensitivity analysis 1) shows how differences in recharge affect groundwater extractions and the dynamics of the state of the aquifer.

Similarly, changes in the supply of surface water affect not only the recharge of the aquifer but also groundwater extractions. A lower supply of surface water implies that the recharge of the aquifer falls while groundwater extractions increase in order to compensate for the reduction in the supply of surface water. Climate change can lead to periods of droughts and floods that have a significant impact on the supply of surface water in the Indus Basin. The dynamics of the state of the aquifer will depend on the variability in the supply of surface water, and we simulate this impact in sensitivity analysis 2.

As with groundwater recharge, spatial differences can also arise in the flow of salt into the aquifer. In the baseline model the majority of the salt that accumulates in the aquifer is through seepage of saline surface water. The salinity concentration of surface water can differ across the basin. In sensitivity analysis 3, we increase the initial average value of the salinity of surface water by 50 percent to examine the dynamics of the aquifer with a higher rate of deterioration of groundwater quality.

The state of the aquifer is also sensitive to exogenous changes in the economic parameters of the model. A lower marginal extraction cost incentivizes greater groundwater extractions and a quicker drawdown of the aquifer in the absence of optimal management. Marginal extraction costs can be lowered artificially by subsidizing the energy cost of running tubewells or through technological change. Sensitivity analysis 4 describes the changes to the baseline model when energy costs of extracting groundwater are lowered by 50 percent.

Exogenous changes in the determinants of revenue (holding all else constant) can also affect extractions. Price subsidies for crops or more intensive cultivation can increase the demand of groundwater and lead to greater extractions. In sensitivity analysis 5 we examined the impact of an exogenous shift in the reduced-form water demand function on the dynamics of the state of the aquifer.

Results of the Tenure Model

Figures 13 and 14 and Table 2 show the dynamics of the water table height under common property management and under optimal control after adapting the baseline model to include tenure. Under common property management, the water table height given by the tenure model falls at a slightly slower rate compared to the water table height under the baseline model. The difference in the water table height given by the two models is negligible in the first 50 years, and when the water table heights given by the two models converge to the steady state—after around 300 years—the water table height under the tenure model is 3 meters higher than the water table height under the baseline model.

Since the water demand function for each farmer is identical, and sharecroppers have an incentive to reduce their input intensity, each sharecropper extracts less groundwater compared to an owner cultivator. The aggregate extractions (extractions of owner cultivators plus the extractions of sharecroppers) under the tenure model will be lower compared to the extractions under the baseline model, and the water table height given by the tenure model falls more gradually compared to the water table height given by the baseline model.

Under optimal management, the dynamics of the water table height given by the tenure model are similar to the dynamics of the water table height given by the baseline model—the differences are too small to appear in the graph. Farmers reduce extractions in the present to receive the benefits of a higher water table and better quality groundwater in the future—optimal extractions are lower than the common property extractions each year. The optimal extractions under the tenure model are less than the recharge rate of the aquifer, and hence the water table level rises each year and converges to a steady state level of 375 meters after about 100 years.

Figure 13: Dynamics of the Water Table Height Under Common Property

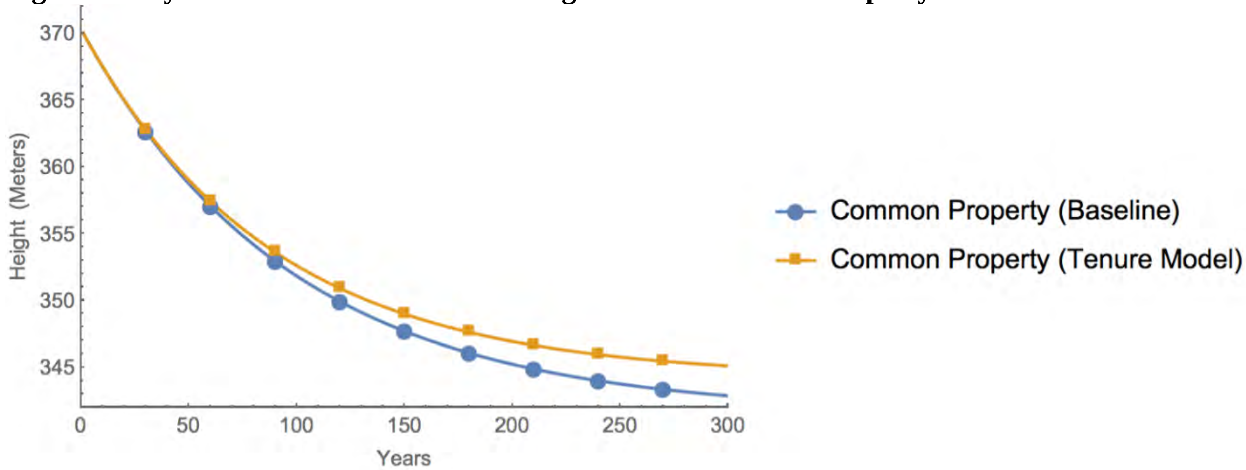
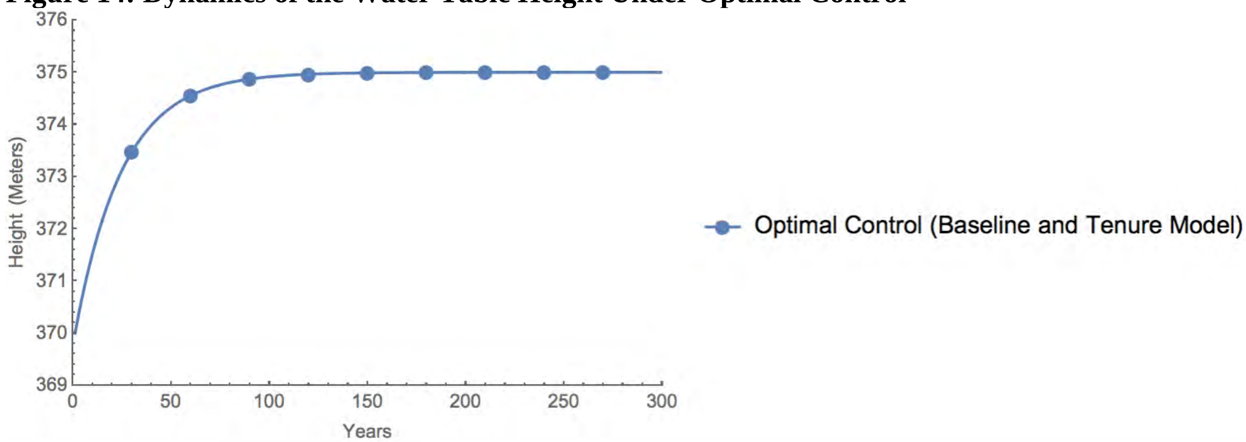


Figure 14: Dynamics of the Water Table Height Under Optimal Control



Figures 15 and 16 below show the long run dynamics of the groundwater salt concentration under common property management and under optimal control. Under the common property regime, the salt concentration level in the first 50 years given by the tenure model is almost the same as the concentration under the baseline model. The groundwater salt concentration evolves according to the height of the water table. The concentration is a function of the volume of groundwater in the aquifer, which in turn depends on the height of the water table. The difference in the height of the water table in the first 50 years is small and so is the difference in the ground water salt concentration in the same period.

Under optimal management, the dynamics of the groundwater salt concentration, given by the tenure simulation, are similar to the dynamics of the groundwater salt concentration under the baseline model—this follows from the results of the dynamics of the water table height. As before, the initial increase in the water table height dilutes the groundwater salt concentration, which starts to gradually increase as the flow of salt mass into the aquifer offsets the increase in volume of the groundwater in the aquifer. This leads to the difference in the concavity of the time paths of the groundwater salt concentration under common property management and under optimal control.

Just as in the baseline case, the groundwater salt concentration under optimal control given by the tenure model is significantly less than the groundwater salt concentration under the common property regime in each period. The concentration is about 2.0 dSm^{-1} after the first 50 years.

Figure 15: Dynamics of the Groundwater Salt Concentration Under Common Property

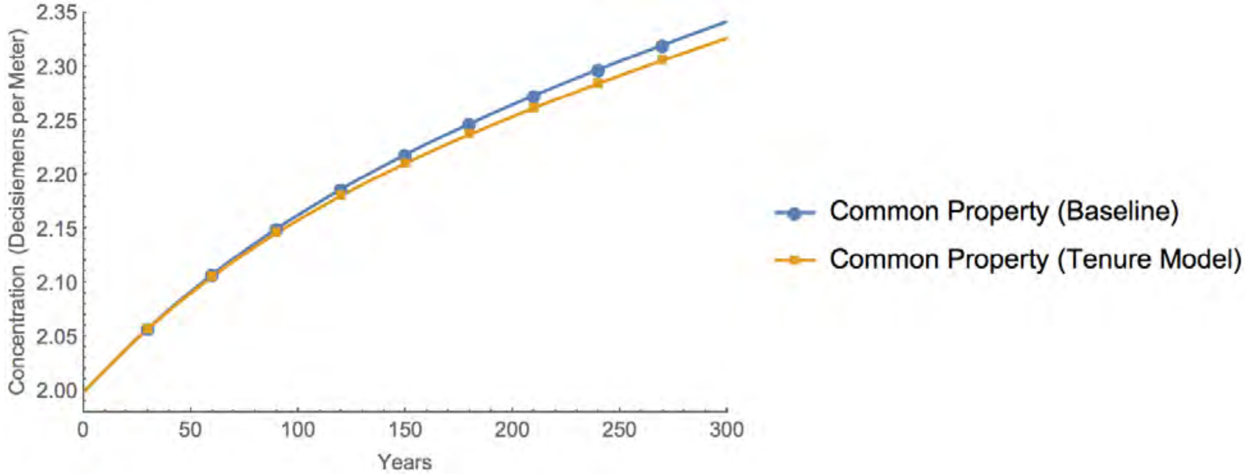
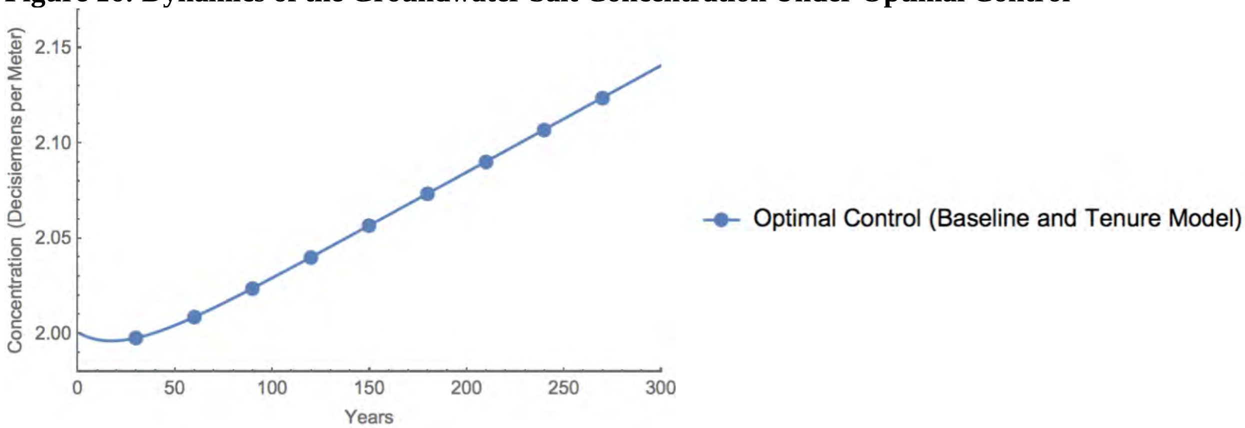


Figure 16: Dynamics of the Groundwater Salt Concentration Under Optimal Control



The corresponding groundwater extractions under common property management and under optimal control are show in Figures 17 and 18 below. The common property extractions given by the tenure model are lower than the extractions under the baseline model. Under the tenure model, sharecroppers have a lower input intensity because of the Marshallian disincentive. The extractions fall over time as it becomes costly to pump groundwater from increasing depths.

The optimal extractions given by the tenure model are similar to the extractions under the baseline model. The present value of future benefits from conserving a unit of groundwater in the present is similar in the baseline model and the tenure model and so are the optimal extractions—optimal extractions are a function of the state variables, which evolve in a similar manner across the two models.

Figure 17: Dynamics of Groundwater Extraction Levels Under Common Property

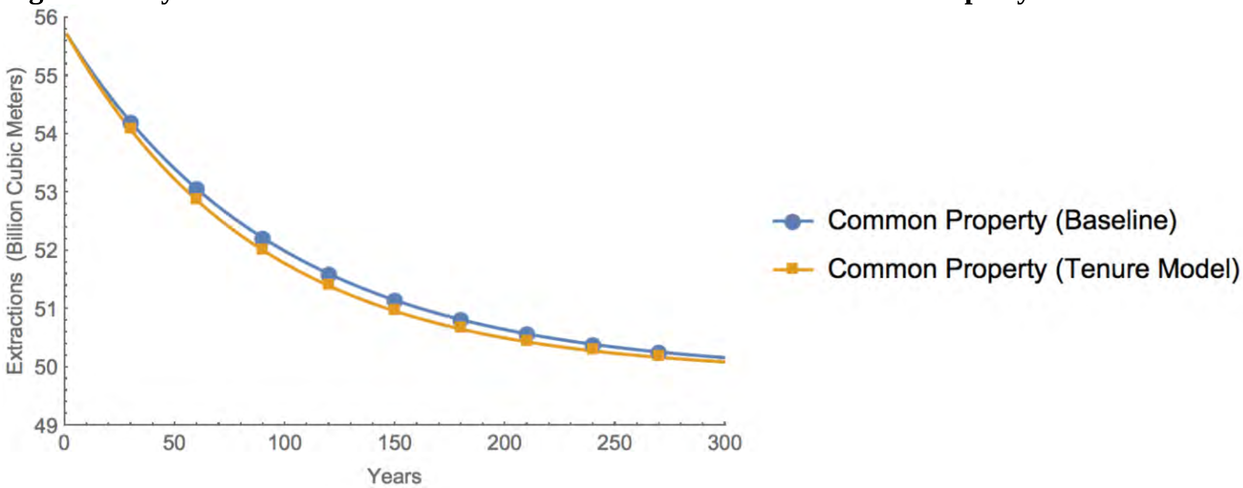
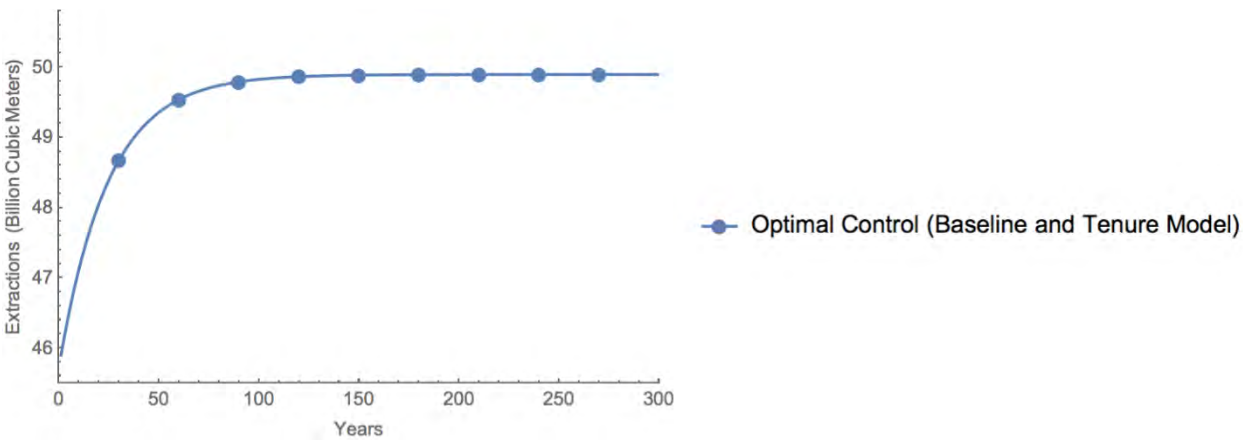


Figure 18: Dynamics of Groundwater Extraction Levels Under Optimal Control



The dynamics of the annual net benefits under common property management and under optimal control are presented in Figures 19 and 20 below. Under common property management, annual net benefits under the tenure model fall over time as the water table height falls and the quality of groundwater deteriorates. Since sharecroppers apply less groundwater than owner cultivators, the net benefits under the tenure model are initially lower than the net benefits under the baseline model—this difference is too small to observe in the graph. However, as the water table height under the tenure model falls more gradually than the water table height under the baseline model, extractions under the baseline model become more costly over time. As the cost of extraction under the baseline model increases more than the cost under the tenure model, the net benefits under the tenure model become greater than the net benefits under the baseline model each subsequent period—the difference becomes noticeable after the first 75 years.

Under optimal control, the differences in the annual net benefits across the tenure model and the baseline model are negligible. The optimal values of the state variables and groundwater extractions are similar across the two models and so are the annual net benefits.

Figure 19: Dynamics of Annual Net Benefits Under Common Property

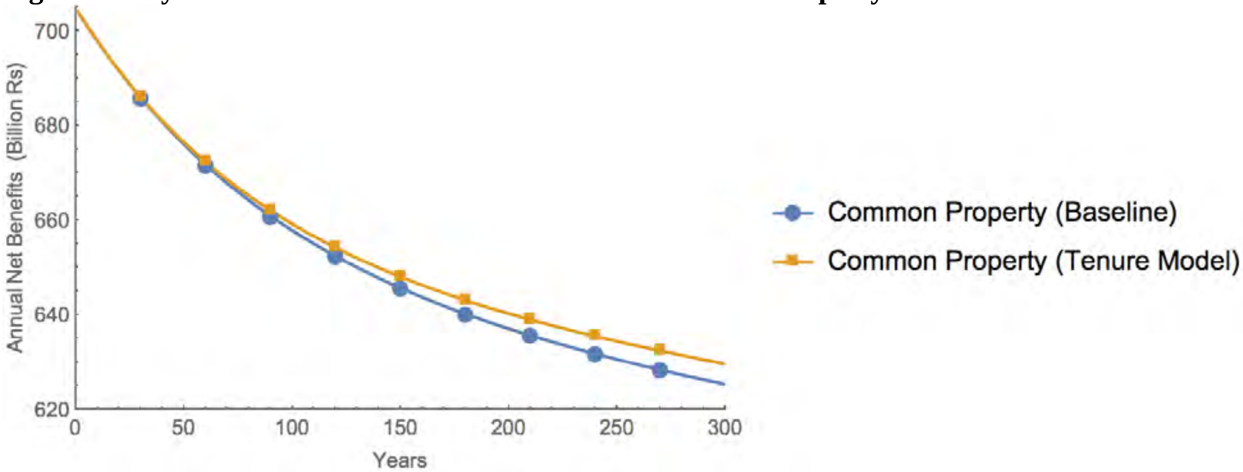
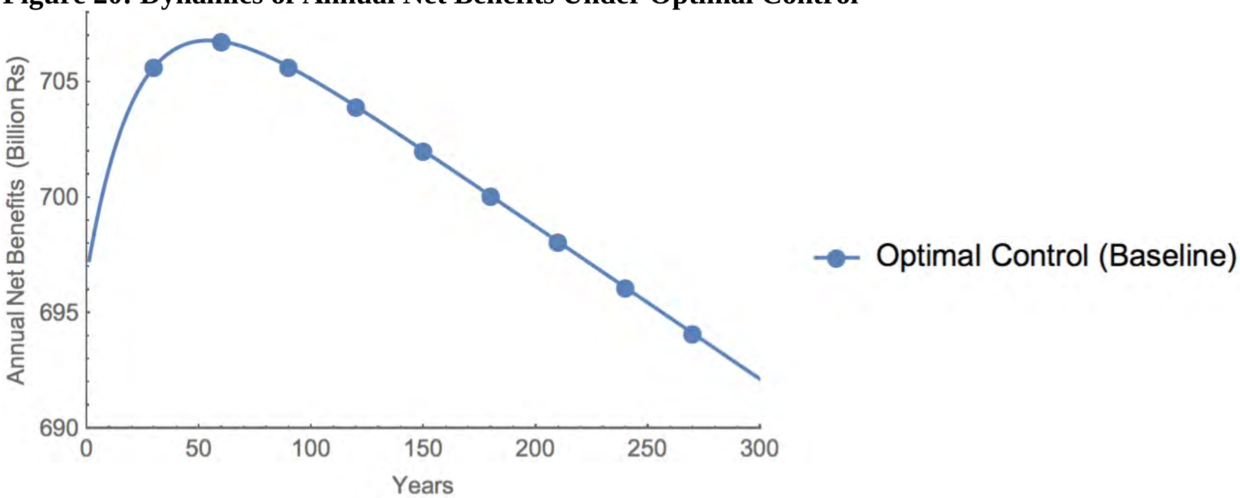


Figure 20: Dynamics of Annual Net Benefits Under Optimal Control



The results of the tenure model show that the inclusion of differences in tenure in the baseline model leads to slightly different common property results and similar optimal control results for the state of the aquifer and groundwater extractions. In the tenure model, output and groundwater cost sharing leads to Marshallian inefficiency—lower groundwater extractions for sharecroppers—which in turn causes a more gradual decline in the water table height compared to the baseline model under common property management. In the absence of Marshallian inefficiency, the model would predict identical results for owner cultivators and sharecroppers.

Under optimal control, the aggregate extractions and the state of the aquifer given by the tenure model are similar to the aggregate extractions and the state of the aquifer given by the baseline model. Even when accounting for the lower input intensity of sharecroppers compared to owner cultivators, the long run benefits of optimal control exceed the benefits of common property management. Regardless of whether or not tenure is included in the model, the results strongly suggest that policymakers in Pakistan should consider optimal management of groundwater over the status quo to ensure the sustainability of the Indus Basin aquifer and to improve the livelihood of rural farmers in the basin.

Table 2: Summary of Results

	Baseline Model		Sensitivity Analysis 1		Sensitivity Analysis 2		Sensitivity Analysis 3		Sensitivity Analysis 4		Sensitivity Analysis 5		Tenure Model	
	CP	OC	CP	OC	CP	OC	CP	OC	CP	OC	CP	OC	CP	OC
First 50 Years														
Water Table Height (Meters)	358.7	374.3	332.4	374.3	315.3	373.8	358.7	374.3	355.1	373.9	338.1	374.4	359.0	374.3
Groundwater Salt Concentration (Decisiemens per Meter)	2.1	2.0	2.2	2.0	2.4	2.0	2.1	2.0	2.1	2.0	2.2	2.0	2.1	2.0
Groundwater Extractions (Billion Cubic Meter)	53.4	49.4	48.0	37.7	55.5	37.8	53.4	49.4	55.2	49.2	59.5	49.4	53.2	49.4
Annual Net Benefits (Billion Rs)	676.0	706.8	621.6	686.4	568.2	646.8	674.5	705.3	687.0	710.0	697.0	767.4	676.4	706.2
First 300 Years														
Water Table Height (Meters)	342.9	375.0	286.7	375.0	238.4	375.0	342.9	375.0	317.5	375.0	298.1	375.0	345.1	375.0
Groundwater Salt Concentration (Decisiemens per Meter)	2.3	2.1	2.7	2.1	3.3	2.1	2.4	2.2	2.5	2.1	2.7	2.1	2.3	2.1
Groundwater Extractions (Billion Cubic Meter)	50.2	49.9	38.7	38.2	39.8	38.5	50.2	49.9	51.4	49.9	50.4	49.9	50.1	49.9
Annual Net Benefits (Billion Rs)	625.3	692.1	519.5	677.6	391.9	639.8	616.3	683.3	612.5	695.6	584.3	752.0	629.6	692.0

Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\ Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\ dSm^{-1}$ (50 percent increase in the salt concentration of surface water); Sensitivity Analysis 4: $\gamma = 0.02\ Rs/m^3.m$ (50 percent reduction in the marginal cost of extraction); Sensitivity Analysis 5: $a_1 = 0.17\ Rs/Bm^3$ (10 percent decrease in the water demand slope under the baseline model).

CP and OC denote Common Property and Optimal Control, respectively.

POLICY INSTRUMENTS AND IMPLICATIONS

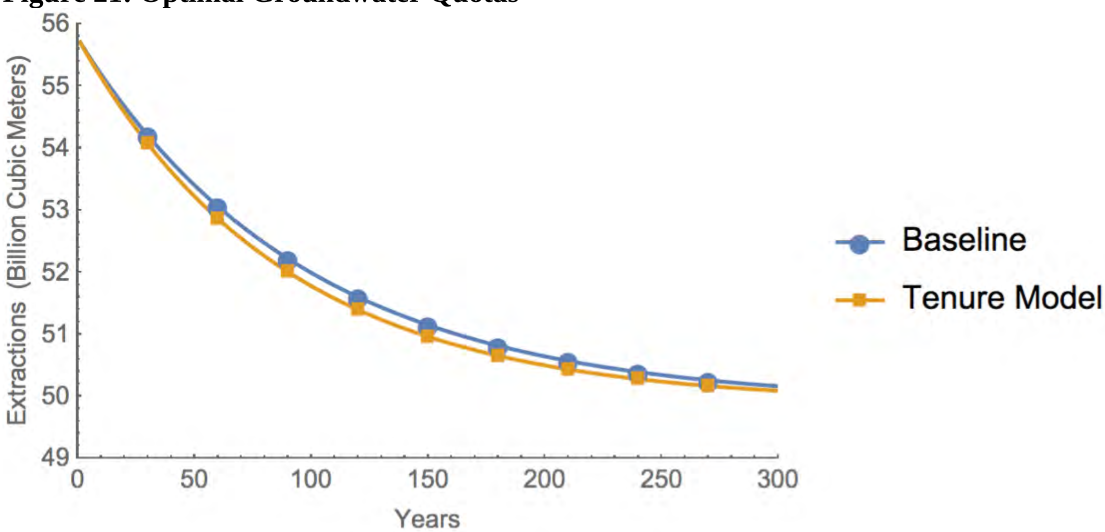
The results in the previous section demonstrate the significant quantitative benefits associated with optimal management of groundwater in the Indus Basin. However, the results so far do not identify how optimal groundwater extractions can be achieved. Under common property management, farmers do not consider the implications of the uncontrolled level of extractions and fail to internalize the resulting externalities. The discussion above shows that there are two externalities associated with the common property management of groundwater: a fall in the water table height and an increase in the groundwater salt concentration. Policy interventions have to address these two externalities by appropriately constraining total groundwater extractions in each period. In this section we discuss quantity and price instruments that can lead to the attainment of the optimal levels of the physical and economic variables.

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, there are no easy solutions to groundwater governance, and groundwater policies have to be adapted according to the socio-political environment of a particular region (Shah, 2014). The policies discussed below are by no means a panacea for the issue of groundwater depletion, but they do provide insight into potential pathways towards devising a larger framework for groundwater governance in the Indus Basin.

Quantity Controls

The analysis of groundwater quantity regulation is fairly straightforward. For the optimal regulation of extractions, the regulator limits extractions in each year to the levels given under the optimal control solutions. Figure 21 below shows the optimal groundwater quotas over time under the baseline model and the tenure model. The quotas are equivalent to the optimal extractions under the two models and have been explained in the previous section.

Figure 21: Optimal Groundwater Quotas



The quota system is a form of command and control policy, which allows the regulator to set limits on the amount of groundwater extractions in each period. For such a policy to be effective, the regulator has to ensure adequate monitoring and enforcement of the quotas and failure to do so can result in farmers extracting groundwater beyond their allowed limit (Shah, 2014). The incentive for farmers to maintain extractions at the optimal level depends on the penalties associated with exceeding quotas and the probability of incurring the penalties. A high penalty for going beyond the allotted extractions and a high probability of enforcing the penalty could create enough of a disincentive for farmers to refrain from cheating.

The feasibility of the groundwater quota system depends on weighing the benefits of optimal management against the costs of establishing a groundwater regulatory body that can effectively monitor and enforce the quotas. Given the large area and number of farms served by the aquifer, the costs of monitoring and enforcement could be prohibitive. However, such costs can be reduced substantially by decentralizing the regulatory authority and empowering local water-user associations (Aarnoudse et al. 2012). The transfer of monitoring and enforcement responsibilities to water-user associations can lead to a more collective effort from local farming communities to sustainably manage their groundwater resources.

Although a properly monitored and enforced quota system can be effective in constraining groundwater extractions, it might not lead to the minimum-cost solution in the presence of substantial heterogeneity in the cost and benefit structures of farmers (Weitzman, 1974). Since the establishment of quotas for each farmer is infeasible, the regulatory authority sets a uniform quota for all groundwater waters users or a sub-group of users—as in the case of owner cultivators and sharecroppers in our discussion. Heterogeneity within the entire group of groundwater users or a sub-group of users can limit farmers' ability to continue production in the most cost-effective manner under a uniform quota policy.

Price instruments provide a cost-effective alternative to quotas. In the following sub-sections we examine pricing policies for the optimal management of the aquifer.

Optimal Tax

Unlike a quota on total groundwater extractions, a tax on per unit extractions leads farmers to adjust extractions so that the marginal benefit of an additional unit of groundwater extraction is equal to the per unit tax. The ability of farmers to adjust extractions when faced with a tax leads to a cost-effective response in a heterogeneous environment. To ensure that groundwater extractions remain at the optimal level, the regulator has to solve for the optimal per unit tax.

Suppose the regulator sets a tax T_t on each unit of groundwater extraction in period t. In a decentralized common property environment where a tax can be charged for extractions, producers maximize:

$$\pi\left(H_t, K_t, Q_{GW_t}\right) - T_t Q_{GW_t} \qquad (37)$$

The first-order condition yields:

$$\frac{\partial \pi}{\partial Q_{GW_t}} = T_t \qquad (38)$$

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 tax per unit of extraction).

Given the Bellman equation in (14) a regulator maximizes the following for optimality:

$$\pi\left(H_t, K_t, Q_{GW_t}\right) + \alpha V(H_{t+1}, K_{t+1}) \qquad (39)$$

Where V is the value function, and the future values of the state variables are calculated using the equations of motion of the water table height and the groundwater salt mass.

Using equation (39) and the definitions of the equations of motion of the state variables, the solution of the optimal groundwater extractions are characterized by the following first-order condition:

$$\frac{\partial \pi}{\partial Q_{GW_t}} = \frac{\alpha(1-\beta_{DP})}{AS_y}\frac{\partial V}{\partial H_{t+1}} \qquad (40)$$

Comparing equations (38) and (40) shows that the optimal tax is given by:

$$T_t = \frac{\alpha(1-\beta_{DP})}{AS_y}\frac{\partial V}{\partial H_{t+1}} \qquad (41)$$

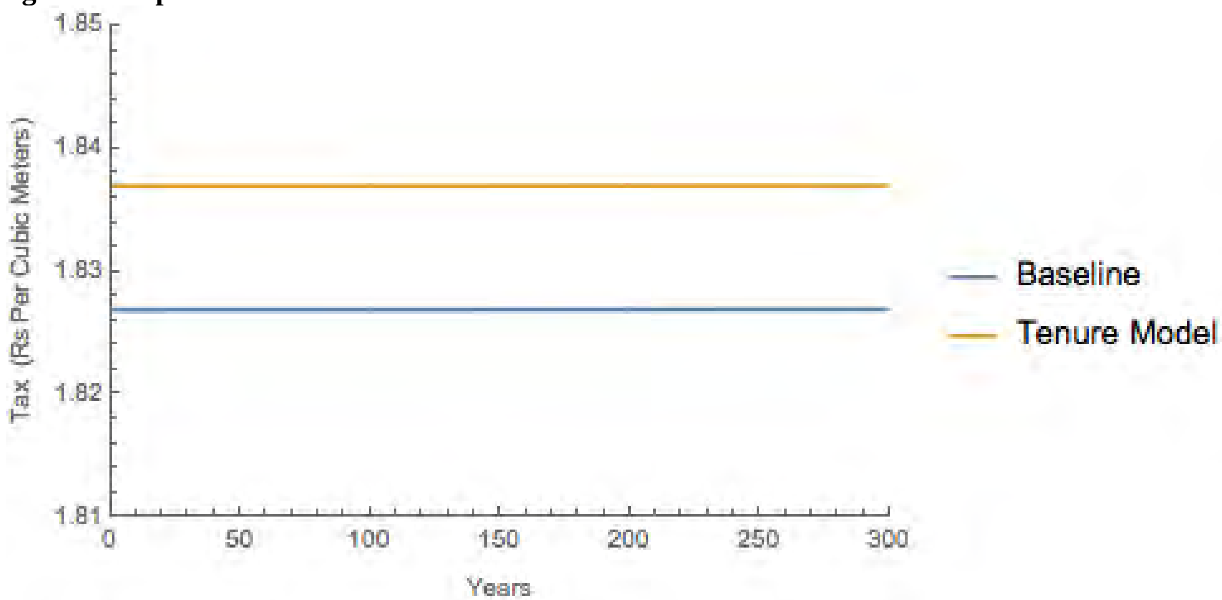
After converting the groundwater salt mass to groundwater salt concentration using equation (7) the optimal tax rate can be expressed as:

$$T_t = \frac{\alpha(1-\beta_{DP})}{AS_y}\left[\frac{\partial V}{\partial H_{t+1}} - \frac{c_{GW_t}}{H_t}\frac{\partial V}{\partial c_{GW_{t+1}}}\right] \tag{42}$$

Note that $\frac{\partial V}{\partial H_t} > 0$ and $\frac{\partial V}{\partial c_{GW_t}} < 0$ since an increase in the water table height leads to greater future net benefits while an increase in the groundwater salt concentration reduces future net benefits.

Figure 22 shows the optimal tax under the baseline and tenure models. In the initial period, the optimal tax under the baseline model is close to Rs 1.83 per cubic meter—the tax revenue at this rate is 12.5 percent of the annual net benefits. The optimal tax under the tenure model is slightly higher than the optimal tax under the baseline model, reflecting the higher scarcity value of groundwater under the tenure model.

Figure 22: Optimal Groundwater Extraction Tax



It is important to note that, in order to ensure equity in the Basin, the tax revenue from optimal management needs to be redistributed to the water users. If the tax revenue is taken away from the sector, the benefits from optimal management can be negligible or even lower than under common property management (Feinerman and Knapp, 1983). For the cooperative benefit of the basin, the tax revenue has to be redistributed back to the 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 lead to an equitable redistribution of the tax revenue. The tax revenue can also be used to invest in modernization of the existing infrastructure for surface water supplies so farmers can reliably substitute groundwater for surface water.

The optimal tax described above is a volumetric tax that works best in environments with a small number of groundwater users whose extractions can be effectively monitored through groundwater metering systems. For aquifers underlying areas cultivated by a large number of users—such as the Indus Basin—the costs associated with the monitoring of extractions and the enforcement of taxes can be substantial (Shah, 2014). In such cases, the tax can be applied indirectly by controlling energy prices—however, a tax on diesel can lead farmers to substitute diesel run tubewells for electricity run tubewells, which would negate the impact of the tax on groundwater extractions. Controlling for the substitution effect of taxation, an indirect tax levied on the price of energy can make the marginal cost of groundwater extraction high enough to reduce extractions in the Indus Basin and limit the overdraft of the aquifer.

In order to maintain extractions at the optimal level, the indirect tax on energy prices would have to be several-fold higher than the current price—a politically unfeasible step that would meet strong resistance from farmers. A combination of direct and indirect taxes on groundwater extractions could be a middle ground for pushing extractions towards the optimal levels. A politically acceptable uniform tax on energy used to run tubewells could be coupled with a tier pricing structure for groundwater extractions (Baerenklau et al. 2014).

Under a tier pricing mechanism, a tax can be levied on extractions exceeding an established threshold. Groundwater extractions beyond the threshold can be divided into several tiers, with an increasing tax rate for each successive tier. Extractions below an established threshold can be exempted from the tax thereby minimizing the burden of taxation on small-scale farmers and subsistence farmers. The tier pricing mechanism could thus ensure equity by transferring the burden of the tax onto large-scale farmers with a heavy reliance on groundwater. However, the monitoring costs of a tier pricing mechanism can also be substantial, which would make its implementation difficult.

Since taxation in the agricultural sector has always been a politically sensitive issue in Pakistan, the government has to take various stakeholders onboard in instituting taxes on groundwater extractions. The regulatory authority can build a consensus around taxation by guaranteeing tax rebates to farmers and assuring a consistent and higher net return on future farm production under the optimal tax regime. The enforcement and collection of taxes can be delegated to local-level water-user associations in order to foster trust and confidence in the regulatory authority's actions.

The empowerment of local water-user associations in the administration of tax collection, enforcement, and management would be a step towards ensuring better management of groundwater in the Indus Basin. The decentralization of tax collection, enforcement, and monitoring would strengthen community involvement in the management of water resources and could limit the transaction costs associated with centralized revenue administration and collection. Enabling farmers to take direct action in managing their water resources would also limit their reliance on a centralized authority. Under local governance, the community itself could be held liable for poor-management and would have an incentive to ensure positive outcomes from management.

Tradable Water Permits

Quotas and taxes on groundwater extractions can be viewed as top down polices. They might meet considerable resistance if farmers are not knowledgeable about the long run benefits that they can receive through optimal management. The establishment of property rights over groundwater and the ability to trade these rights offers a market-based system for controlling groundwater extractions (Zilberman et al. 1994). The government, in this case, provides a regulatory and legal framework for the exchange of property rights. The allocation of rights, however, is determined by the private exchange of the rights to groundwater in a fully functioning market.

Under a market system for groundwater rights, the government establishes a given number of permits for the right to extract a specified amount of groundwater during a certain period of time. Given the high transaction costs of planning, setting quotas for five or ten year periods might be more practical than doing so on a yearly basis. For optimal management, the permits would correspond to the optimal levels of groundwater extractions explained earlier (Figure 21). The permits would be divided across groundwater-users according to an established rule such as acreage (a set number of permits per acre) or surface water reliability (more permits for farms with inadequate supply of surface water). Farmers are then allowed to trade these permits with each other in a market established for these permits.

Under a fully functioning ground water permit market without significant transaction costs, farmers would trade permits to a point where the price of a permit equals the additional benefits of using an additional unit of groundwater (Latinopoulos and Sartzetakis, 2011). This price corresponds to the optimal tax rate discussed in the last subsection. The market ensures that the permits are allocated efficiently across farmers, and the aggregate extractions in equilibrium equal the optimal level, since the number of permits distributed corresponds to the optimal levels.

The functioning of a groundwater permits market depends on the size and nature of the transaction costs of trading permits. In the absence of transaction costs, groundwater permits would be allocated efficiently across farmers after all gains from trade are exhausted. In reality, transaction costs in the market for groundwater permits are probably high enough to lead to an inefficient allocation of permits and cause extractions to exceed the desired levels (Koundouri, 2004). In a setting such as the Indus Basin, transaction costs in the market for groundwater permits could be minimized by creating localized markets that are easily accessible to farmers.

Groundwater permit markets also have to be regulated by strong local institutions to facilitate transactions. Dissemination of information regarding local water resources and the benefits of optimal management by these institutions can encourage community participation in the permits markets and allow farmers to play an active role in managing their water resources. Local institutions would also have to ensure effective monitoring and enforcement of the groundwater extractions permitted under their jurisdiction. Rewarding farmers for keeping extractions within the permissible level can incentivize compliance with the established rules and regulations of the institutions.

In this section we have described three policies that could lead to the optimal levels of groundwater extractions each year and limit the overdraft of the aquifer in the Indus Basin. The discussion showed that quotas on extractions and price instruments, such as extraction taxes and tradable ground water permits, are direct methods of limiting extractions at the optimal levels. However, the feasibility and implementation of these polices depends on the transactions costs associated with monitoring and enforcement and requires a broader understanding of the socio-economic and political environment of the region. The analysis presented here provides quantitative and qualitative information that can be useful in devising a comprehensive governance structure for water resources in the Indus Basin.

SUMMARY AND CONCLUSIONS

In this paper we presented a hydrological-economic model of groundwater extractions in Pakistan's Indus Basin and analyzed the long-run dynamics of the water table height, groundwater salt concentrations, groundwater extractions, and net benefits under two types of management schemes: common property management and optimal management. Under common property management (the status quo in the Indus Basin), farmers are considered myopic in their decision to extract groundwater in the sense that their production decision in the present period does not account for the impact of the state of the aquifer on future farm benefits. Under optimal management, a social planner explicitly considers the cost of present groundwater extractions on the discounted net benefits in the future. The optimal management solution forces farmers to account for not only the marginal extraction cost of groundwater but also the marginal user cost of groundwater—the present value of the loss in net benefits in the future given a unit of groundwater extraction in the present.

The baseline results showed that under common property management, the state of the aquifer deteriorates over time and net benefits fall as a result. The water table height falls by 12 meters in the first 50 years, while the groundwater salt concentration increases by 0.09 dSm^{-1} in the same period. The deterioration in the groundwater salt concentration translates into a 1.25 percent reduction in the annual net benefits. Groundwater extractions fall over time as both the water table height and the quality of groundwater decline, thereby increasing the costs of extraction. Groundwater extractions exceed the recharge of the aquifer in each period so that the water table height in the subsequent period falls. The fall in the water table height decreases the volume of groundwater in the aquifer. Since seepage of saline surface water and rainwater brings a constant flow of salt mass into the aquifer, the decrease in the volume of groundwater in the aquifer leads to a gradual deterioration of groundwater quality. As a result of the declining water table and an increase in the groundwater salt concentration, net benefits fall by around Rs 30 billion in the first 50 years.

The optimal management problem is solved using dynamic programming, and the results show that optimal extractions are less than the recharge of the aquifer leading to a gradual increase in the water table height. The water table height reaches the steady state in about 100 years at the boundary constraint of 375 meters (5 meters below land elevation). The groundwater salt concentration falls initially as the increase in the volume of groundwater in the aquifer dominates the increase in the flow of salt mass into the aquifer. After about 25 years, the effect of increasing the total salt mass dominates the effect of rising groundwater in the aquifer, and the groundwater salt concentration begins to increase. However, the groundwater salt concentration remains well below the concentration levels under common property management in each period. The rising water table height and better quality groundwater leads to an increase of about Rs 10 billion in net benefits after the first 50 years. At this horizon, the annual net benefits under optimal management are Rs 35 billion higher than the annual net benefits under common property management.

We also conducted five sensitivity analyses to see the impact of changes in the hydrological and economic parameters on the long run dynamics of the state of the aquifer, groundwater extractions, and annual net benefits.

Since hydrological and economic parameters in our model do not vary across space, the sensitivity analyses allowed us to examine changes in the aggregate baseline results that could result from spatial differences in the parameter values. Some of the results were quite sensitive to the parameter values used in the analyses.

The results of the sensitivity analyses showed that under common property management, the rate of decline of the water table is related to the magnitude of total groundwater recharge—the lower the recharge the quicker the fall in the water table height. Moreover, as net benefits from groundwater usage increase, the water table height falls more rapidly. A reduction in surface water leads to greater groundwater extractions and a significant decline in the water table height.

We also found that given the high value of the discount factor, the steady state optimal control solutions for the water table height in all the sensitivity analyses are almost identical. The optimal groundwater concentrations remain well below the concentration levels under common property management. The annual net benefits from optimal control exceed the annual net benefits from common property management after about 20 years under most sensitivity analyses.

Differences in tenure arrangements in agriculture can affect groundwater extraction decisions. We adapted the baseline model to include differences in extractions across owner cultivators and sharecroppers. We observed very small differences in the common property results for the long run dynamics of the state of the aquifer and groundwater extractions between the tenure model and the baseline model. In the tenure model, sharecroppers exhibit Marshallian inefficiency and have lower extractions compared to owner cultivators which leads to a more gradual decline in the water table height. Since the groundwater salt concentration depends on the water table height, we observe better groundwater quality in the tenure model than in the baseline model. The differences in the baseline model and the tenure model were quite small because of the low proportion of sharecroppers among all farmers (10 percent) and the small effect of the Marshallian inefficiency on groundwater extractions.

We described a set of quantity and price instruments that could be used to limit extractions to the optimal levels. Quantity instruments include quotas on groundwater extractions, which can be set each year—or for longer periods of time—at the optimal levels of extraction. However, the administrative costs of monitoring and enforcing quotas can be substantial. Price instruments include taxes on groundwater extractions and a market for groundwater permits. Using the optimal control results, we derived the long run tax rates that could induce farmers to reduce extractions to the optimal levels. To make the tax policy more appealing to farmers, the revenue from taxation on extractions could be reinvested back in the sector as long as the rebate does not incentivize extractions.

Under a market for groundwater permits, farmers trade their allotted permits until all gains from trade are exhausted. In the absence of transaction costs, the equilibrium price of permits should equal the optimal tax rate, and the market will allocate the permits efficiently. In a setting such as the Indus Basin with close to 800,000 groundwater users, trading of ground water permits would entail significant transaction costs; which can be minimized by having a strong regulatory framework that facilitates the trading of permits. A fully functioning market for groundwater markets needs to be regulated by a combination of a strong central authority and community-based institutions. Allowing local institutions to manage markets for groundwater permits with effective oversight from a central authority could reduce transaction costs in the trading of permits.

The policies that we described are not a panacea for issues related to excessive groundwater use and aquifer depletion in the region. Monitoring costs are likely to be high, creating obstacles for the implementation of these policies. The socio-economic and political environment is important in determining the right set of policies and in tailoring them to local needs. Our analysis, however, does provide important qualitative and quantitative information that can used to assist in devising a long-term strategy for the effective governance of the water resources in the Indus Basin.

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