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Allocative Efficiency and Optimal Management of Groundwater in Pakistan's Agricultural Sector

A dissertation submitted in partial satisfaction
of the requirements for the degree of

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in

Environmental Sciences

by

Sanval Nasim

December 2015

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I often reflect on my first conversation with Ariel Dinar—he called me before I had been accepted into the PhD program for an informal conversation—and remember feeling nervous, yet excited, about working with someone with a wealth of experience as a water economist, but who had only recently joined academia. After I arrived in Riverside and met Ariel, my nervousness dissipated almost immediately. From our very first meeting, Ariel has been a dedicated teacher and a patient mentor. He has given me the intellectual space to pursue my work independently but has stepped in as a guiding force when necessary. I only hope to emulate his abilities as a teacher and researcher as I move forward in my career.

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To Anum,

the brightest star in the sky.

And to Shahnaz, Anjum and Savail,

for their unyielding love, support and encouragement

throughout this journey.

ABSTRACT OF THE DISSERTATION

Allocative Efficiency and Optimal Management of Groundwater in Pakistan's Agricultural Sector

by

Sanval Nasim

Doctor of Philosophy, Graduate Program in Environmental Sciences
University of California, Riverside, December 2015
Dr. Ariel Dinar, Co-Chairperson
Dr. Steven M. Helfand, Co-Chairperson

This dissertation comprises three studies on Pakistan in which I examine the allocative efficiency of groundwater across farm-level constraints; the optimal management of groundwater given differences in agricultural tenure; and the effect of a set of policies on the utilization of groundwater. In the first chapter, I estimate the allocative inefficiency of groundwater in Pakistani agriculture using a panel dataset of rural households and show that the utilization of groundwater varies across a set of farm-level constraints (tenure, farm size, access to surface water and location on a watercourse). In the second chapter, I examine the long-run trend of groundwater depletion in Pakistan's Indus Water Basin under common-pool resource management—the status quo—and under optimal management. I develop a dynamic optimization problem to illustrate long-run steady states of groundwater pumping under different management, hydrologic, economic and tenure assumptions. The analysis shows that the benefits of optimal management exceed the benefits of common property management, and that the small share of sharecropping does not have an important effect on the results. In the third chapter, I use a panel dataset of rural households—the same dataset used in the analysis in the first chapter—to examine the effects of two water policies—increasing access to surface water and increasing the reliability of the supply of surface water (as measured by being located higher up on a watercourse)—on the allocative efficiency of groundwater and land productivity. The results show that farms allocate groundwater more efficiently (over utilization decreases) as the share of total farm area with access to surface water increases while increasing the reliability of surface water supply does not appear to improve the utilization of groundwater. Increasing the share of total area with access to surface water has a modest effect on land productivity. My research emphasizes the relationship between groundwater conservation and the institutional environment of farms in Pakistan's agricultural sector, and helps to inform the larger discussion on the effective governance of water resources in the region.

Table of Contents

List of Figures

List of Tables

Introduction

Motivation

Irrigation water is a major input in agricultural production in many countries in arid and semi-arid regions 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 kilometres of main canals, over 600 thousand tubewells, and 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 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 in the country 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 deterioration of groundwater quality 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).

Farm-level constraints affect the degree and efficiency of utilization of water in Pakistan's agricultural sector (Briscoe and Qamar 2006). Some of the farm-level constraints that could lead farmers in Pakistan to misallocate inputs include, but are not limited to: agricultural tenure, farm size, access to irrigation water, location on watercourse, access to credit, cultivation experience and access to water user associations. Differences in incentives across these farm-level constraints may explain an important part of Pakistan's water-management issues (Dinar et al. 2004).

Pakistan has a vibrant agricultural sector spread across its four provinces with wheat, cotton, rice, and sugarcane constituting the bulk of agricultural production. Pakistani agriculture is characterized by a diversity of tenure arrangements that reflect the risks and constraints that farmers face. Agricultural tenure falls under three basic categories: owner-cultivators, fixed-rent tenants, and sharecroppers. According to *Government of Pakistan Statistics Division (2003)*, owner-cultivators operate approximately two thirds of the total cultivable land. Since Pakistan's independence in 1947, state and market-assisted land reforms as well as other economic forces have led to a decline in sharecropping and a rise in owner-cultivated land (Cheema and Nasir, 2010). The incentives for efficient allocation of resources under each form of tenure differ, and consequently production and input-use decisions vary across tenure as well.

Most farmers in Pakistan supplement surface water with groundwater, and the share of groundwater in irrigation has increased significantly in the last two decades (Qureshi et al., 2004). Yet the degree of utilization of both sources of irrigation depends on many farm-level factors. To help achieve the goals of Pakistan's economic growth strategy, a comprehensive analysis is needed to identify the factors that influence the efficiency of utilization of all types of irrigation water in the country and to formulate policies that could lead to an improved allocation of irrigation water.

One way of measuring the extent of Pakistan’s water-management problem is through estimating the allocative efficiency of irrigation water across a set of farm-level constraints. Allocative efficiency reveals the degree of over- or under-utilization of inputs, given their prices. It measures the ability of a firm to use inputs in optimal proportions, given their prices and the existing production technology (Coelli et al. 2005). Technical efficiency, in contrast, reflects the ability of a firm to produce the maximum output from a given level of inputs. Estimation of input-specific allocative inefficiency explains the degree of utilization of each input. Quantifying the differences in input-use across farm-level constraints could help policymakers target input-conservation policies towards farmers facing specific constraints.

Moreover, 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 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 differences in tenure. A dynamic groundwater extraction model that simulates the long-run trend of the water table height and its impact on farm profits could help policymakers to formulate appropriate groundwater-conservation policies.

Description of Chapters

This dissertation comprises three studies on Pakistan's irrigated agriculture in which I examine the allocative efficiency of groundwater across farm level constraints; the effect of a set of policies on the utilization of groundwater, and the optimal management of groundwater given differences in agricultural tenure. The studies emphasize the relationship between groundwater conservation and the institutional environment of farms in Pakistan's agricultural sector. The analysis in this dissertation helps inform the larger discussion on the effective governance of water resources in the region.

In the first chapter, "Allocative Inefficiency and Farm-Level Constraints in Irrigated Agriculture in Pakistan", I estimate the allocative inefficiency of groundwater in Pakistani agriculture and compare it across a set of farm-level constraints, using a panel dataset of rural households. The farm-level constraints include tenure, farm size, access to surface water and location on a watercourse. I use a stochastic approach, based on a system of equations to estimate both the technical efficiency of farms and the allocative efficiency of groundwater use. The allocation of surface irrigation water in Pakistan is fixed per unit of land, so its allocative inefficiency cannot be estimated. Therefore, I treat surface water as a fixed factor and focus mainly on groundwater. The analysis sheds light on the utilization of irrigation water across a set of farm-specific characteristics. It also provides a basis for a possible redesign of water policy.

In the second chapter, "Optimal Groundwater Management in Pakistan's Indus Water Basin", I 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. I develop a dynamic optimization problem to illustrate long-run steady states of groundwater extraction under different management, hydrologic, economic and tenure assumptions. Whereas the focus of the previous chapters was on farm-level utilization and allocation of groundwater in Pakistan, this chapter emphasizes the sustainability of Indus Water Basin aquifer under different groundwater management schemes. I 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 provides a framework to develop and discuss policies that could lead to the optimal management of groundwater.

The third chapter, "Simulating the Effects of Water Policies on the Allocative Efficiency of Groundwater and Land Productivity in Pakistan", builds on the analysis in Chapter 1. I use a panel dataset of rural households—the same dataset used in the analysis in Chapter 1—to examine the effects of two water policies—increasing access to surface water and increasing the reliability of the supply of surface water (as measured by being located higher up on a watercourse)—on the allocative efficiency of groundwater and land productivity. From a policy perspective, increasing access to surface water and ensuring a reliable supply of surface water might improve the utilization of groundwater as suggested by the results in Chapter 1.

I first use stochastic frontier analysis—based on a system of equations—to estimate the allocative efficiency of groundwater use. In contrast to the estimation strategy in Chapter 1, I include a set of explanatory factors of allocative efficiency of groundwater in the estimation in chapter 2, including access to surface water and location on a watercourse. Using the estimation results, I determine the appropriate policies for improving the utilization of groundwater, and then simulate, using a range of parameters, the effects of those policies on the allocative efficiency of groundwater. I then quantify the effect of the change in the allocative efficiency of groundwater on land productivity. The analysis sheds light on factors that improve the utilization of groundwater and consequently increase land productivity.

Summary of the Findings

The utilization of groundwater differs considerably across various farm-level constraints:

- Farms with access to both surface water and groundwater allocate groundwater more efficiently than farms that have access to only groundwater. Farms with only groundwater do not have any additional source of irrigation to meet their water requirements and might over utilize groundwater.
- On average, owner-cultivators and fixed-rent tenants over utilize groundwater while sharecroppers underutilize it. The underutilization of groundwater by sharecroppers might be driven by the fact that a high share of sharecroppers has access to surface water compared to owner cultivators.
- Farms located at the head of the watercourse and farms located at the middle of the watercourse tend to be more allocatively efficient than farms located at the tail of the watercourse. Farms at the tail of a watercourse might over utilize groundwater to compensate for the unreliable supply of surface water.

The benefits under optimal management exceed the benefits under common property management:

- Under common property management, groundwater extractions exceed the recharge of the aquifer and the water table height falls over time until it reaches a steady state. The groundwater salt concentrations increase over time due to the decrease in the volume of groundwater in the aquifer. The gradual fall in the water table height and deterioration of groundwater quality lead to a decrease in net benefits over time.
- Under optimal management, the high marginal user cost of groundwater causes groundwater extractions to be lower than the recharge of the aquifer. The water table height increases over time and reaches a steady state at the boundary condition. Groundwater quality improves initially as the water table height increases, but then deteriorates when the increase in salt mass exceeds the increase in the volume of groundwater in the aquifer. Net benefits increase initially but then fall as groundwater quality deteriorates.

Small effect of existing tenure arrangements on different groundwater management schemes:

- In the tenure model (which includes owner cultivators and sharecroppers), output and groundwater cost sharing leads to Marshallian inefficiency—lower groundwater extractions for sharecroppers. The 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 (includes only owner cultivators) were small. 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. The small share of total sharecroppers (10 percent) leads to the lack of significant differences between the results of the two models.

Water policies that improve the utilization of groundwater have a modest effect on land productivity:

- Farms allocate groundwater more efficiently (over utilization decreases) as the share of total farm area with access to surface water increases. Increasing access to surface water is a potential policy that can improve the utilization of groundwater and increase land productivity.
- Increasing the reliability of surface water supply (as measured by being located higher up on a watercourse) does not appear to improve the utilization of groundwater.
- Increasing the share of total area with access to surface water has a modest effect on land productivity—a maximum of 0.1 percent increase in income per hectare due to a 36 percent increase in the mean value of the share of total farm area with access to surface water.
- Suggested policies, nonetheless, are important in ensuring equity in the distribution of surface water.
- Further research is required to ascertain the impact of a more reliable and equitable distribution of surface water in improving rural livelihoods.

Chapter 1: Allocative Inefficiency and Farm-Level Constraints in Irrigated Agriculture in Pakistan

1.1 Introduction

Pakistan has a vibrant agricultural sector, spread across its four provinces, with wheat, cotton, rice, and sugarcane constituting the bulk of agricultural production. Pakistan's economic growth strategy, as laid out in the report *Pakistan: Framework for Economic Growth 2011,* emphasizes irrigation water reform as one of its goals to enhance agricultural productivity and stresses the urgent need to conserve irrigation water. Ineffective water-management policies in the past have affected water availability, water quality and soil quality.

Moreover, farm-level constraints affect the degree and efficiency of utilization of water in Pakistan's agricultural sector (Briscoe and Qamar 2006). Some of the farm-level constraints that could lead farmers in Pakistan to misallocate inputs include but are not limited to: tenure, farm size, access to irrigation water, location on watercourse, access to credit, cultivation experience and access to water user associations.[1] Differences in incentives across these farm-level constraints may explain an important part of Pakistan's water-management issues (Dinar et al. 2004).

Most farmers in Pakistan supplement surface water with groundwater, and the share of groundwater in irrigation has increased significantly in the last two decades

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[1] Agricultural tenure falls under three basic categories: owner-cultivators, fixed-rent tenants, and sharecroppers. According to the Government of Pakistan Statistics Division (2003), owner-cultivators operate approximately two-thirds of the total cultivable land.

(Qureshi et al. 2004); however, the degree of utilization of both sources of irrigation water depends on many factors. Since most tubewell pumps utilized to extract groundwater in Pakistan are diesel-operated, the price of groundwater in Pakistan varies with the price of diesel and is relatively high (Shah et al. 2009). The degree of utilization of groundwater and surface water also depends on access to capital, which is influenced by the overall institutional environment of farms. To help achieve the goals of Pakistan's economic growth strategy, a comprehensive analysis is needed to identify the factors that influence the efficiency of utilization of irrigation water in Pakistan and to formulate policies that could lead to a more optimal allocation of irrigation water.

Given the differences in incentives across farm-level constraints, one way of examining Pakistan's water-management problem is through estimating the allocative efficiency of irrigation water across a set of farm-level constraints. Allocative efficiency reveals the degree of over- or under-utilization of inputs, given their prices. It measures the ability of a firm to use inputs in optimal proportions, given their prices and the existing production technology (Coelli et al. 2005). Technical efficiency, in contrast, reflects the ability of a firm to produce the maximum output from a given level of inputs.

Studies on Pakistani agriculture (Battese et al. 1996; Ali et al. 1994) have generally focused on overall technical and allocative efficiency of farms and have not compared input-specific allocative inefficiencies across farm-level constraints. Failure to account for input-specific allocative inefficiency might lead to biased estimates if the inputs are correlated with the error term (Kumbhakar and Lovell 2000). Estimation of input-specific allocative inefficiency explains the degree of utilization of each input.

Quantifying the differences in input-use across farm-level constraints could help policymakers target input-conservation policies towards farmers facing specific constraints.

In this study, I estimate the allocative inefficiency of groundwater in Pakistani agriculture and compare it across a set of farm-level constraints, using a panel dataset of rural households. The farm-level constraints include tenure, farm size, access to surface water and location on a watercourse. I use a stochastic approach, based on a system of equations to estimate both the technical efficiency of farms and the allocative efficiency of groundwater use. The allocation of surface irrigation water in Pakistan is fixed per unit of land, so its allocative inefficiency cannot be estimated. Therefore, I will treat surface water as a fixed factor and focus mainly on groundwater. The analysis sheds light on the utilization of irrigation water across a set of farm-specific characteristics. It also provides a basis for a possible redesign of water policy. The results in this study constitute the empirical basis for policy work that I will focus on in my future work.

This chapter is organized as follows: Section 1.2 reviews various approaches used in the literature to measure allocative inefficiency. Section 1.3 develops a model of allocative inefficiency and presents the estimation strategy. In section 1.4, the data from two waves of the Pakistan Rural Household Survey[2] are discussed and descriptive statistics on agriculture and water across two provinces – Punjab and Sindh – are compared. Section 1.5 explains the creation of the panel dataset for Punjab and Sindh, and the construction of the variables used to estimate allocative inefficiency. Section 1.6

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[2] I would like to thank the Pakistan Institute of Development Economics (PIDE) for assistance in obtaining the two waves of the Pakistan Rural Household Survey that are used in this study.

discusses the estimation results. Section 1.7 concludes and addresses some of the policy implications of the findings.

1.2 Review of Stochastic Frontier Approaches

1.2.1 The Econometric Approach to Examining Efficiency

Productivity and efficiency analysis can be conducted using non-parametric and parametric approaches. The non-parametric approach includes data envelopment analysis (DEA) that uses linear programming techniques to confine observed data within the smallest possible convex set. The advantage of DEA is that a functional form for the production function does not need to be specified *a priori*. The disadvantage is that all deviations from the frontier are assumed to be a result of technical inefficiency and, thus, it leaves no scope for measurement and random error. The parametric approach includes econometric methods to estimate production, cost, and profit functions. Assumptions must be made about the functional form, but the approach can accommodate measurement and random error. This approach is often preferable for analyzing efficiency in agriculture because unobserved random factors affect agricultural production, and farm-level data usually contain considerable measurement error.

The econometric analysis of efficiency begins with the estimation of a frontier, based on the theoretical aspects of production, cost, and/or profit functions. The frontier, therefore, reflects either the maximum attainable output, given a set of inputs (production frontier); the minimum cost of producing output, given the prices of inputs (cost frontier); or the maximum profit that can be attained, given output and input prices (profit frontier).

In all cases, technology and fixed factors are also considered a given. The frontier represents an ideal locus in the sense that no agent can exceed it. In this context, the measurement of inefficiency is the estimation of the difference between observations and the best-practice frontier (Greene 2008).

The econometric models of frontier analysis can be either deterministic or stochastic. In the former case, deviations from the frontier are considered solely the result of inefficiency. Stochastic frontier analysis considers deviations from the frontier to be a consequence of inefficiency and random factors outside the control of the agents. It incorporates measurement error and other statistical noise, and allows for the estimation of more precise measures of inefficiency.

Generally, stochastic models include a deterministic component, a non-negative random variable for inefficiency, and a symmetric random error term to capture statistical noise. Observed outputs tend to lie below the deterministic part, and they can only lie above if the noise effect dominates the inefficiency effect.[3]

Production, cost, or profit frontiers can be estimated either as a single equation or as a system of equations. In the single equation estimation, inputs and outputs (if a profit frontier) are treated as exogenous. However, inputs and outputs are a function of their relative prices, and treating them as exogenous biases the parameters of the estimated frontier. A system of equations method allows the simultaneous estimation of the production, profit, or cost frontier, and input demand and output supply equations. The

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[3] See Coelli et al. (2005).

input demand and output supply equations are derived by imposing a specific behavioral assumption on the producers, as discussed below.

A stochastic profit frontier applies to situations in which the behavioral objective of producers is to maximize profits. Profit-maximizing producers face exogenous input and output prices, and their input and output functions are determined endogenously. Stochastic profit frontier analysis can be divided into the primal and dual approaches. In the primal approach, a stochastic production function is used and the output supply and input demand functions are determined through the first-order conditions of profit maximization. Parameters of this system of equations are then estimated. In the dual approach, a profit function is stated and Hotelling's lemma is applied to derive the input and output share equations. Parameters are then estimated using this system of equations. Allocative inefficiency in this context is measured as the extent to which the first-order conditions of profit maximization fail to hold.[4]

1.2.2 Applications of Stochastic Frontier Analysis

Stochastic frontier analysis has been used extensively to examine the efficiency of firms in a variety of settings. Below I review some recent applications of stochastic frontier analysis in agriculture.

Liu and Myers (2009) estimate a stochastic production frontier for maize growers in Kenya under different functional forms. They also incorporate exogenous factors that

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[4] Allocative inefficiency in the profit frontier approach can be different from allocative inefficiency in the cost frontier approach. The difference lies in the first-order conditions of the two objectives. In the cost approach, allocative inefficiency is given by the departure of the marginal rate of substitution (between two inputs) from the ratio of the input prices. In the profit approach, allocative inefficiency represents the departure of the marginal product (of an input) from its normalized price (ratio of input and output prices).

affect technical efficiency in their production function. Their results show that the magnitude of efficiency estimates and the effect of exogenous factors on efficiency differ across specifications. However, the efficiency ranking remains largely constant across all specifications. Exogenous household characteristics account for only 10 percent of the variation in efficiency. They find that education, non-farm income, and farm size increase technical efficiency, while female-headed households, distance from a bus stop (used as a proxy for transactions costs), and owned land (versus rented) decrease it.

Revoredo-Giha et al. (2009) use panel data on 358 Scottish farms to examine cost efficiency in a stochastic cost frontier framework. They find a wide variation in the cost-efficiency levels within and between different farm-type groups. Also, farms that have been heavily supported by subsidies demonstrate the greatest variation in cost efficiency. They also regress cost efficiency against exogenous farm-level factors and find that their effect on cost efficiency differs across types of farms.

Abdulai and Tietje (2007) use panel data on 149 farms in northern Germany to estimate several stochastic production frontiers (under different specifications) and technical efficiency while accounting for farm-level heterogeneity. They show that a random-effects model produces biased estimates, while the fixed-effects model can be considered consistent and a benchmark for comparison with other models. Also, time-invariant models underestimate efficiency, while time-variant models were not sensitive to firm-specific heterogeneity.

Idiong (2007) estimates a stochastic production frontier to analyze the technical efficiency of small-scale rice producers in Nigeria. The author obtains a mean efficiency score off 77 percent, suggesting that farmers can improve technical efficiency by 23 percent. The author also regresses the efficiency estimates on exogenous farm-level factors and finds that education, membership in a cooperative association, and access to credit greatly improve efficiency.

Chen et al. (2009) also estimate a stochastic production frontier for Chinese farms across four regions. They find that the four production frontiers have statistically different structures and that the marginal products of the inputs differ across regions as well (including overuse of labor), implying that the allocation of inputs did not meet an efficiency standard across regions. They also suggest that using machinery and eliminating land fragmentation could increase technical efficiency. Moreover, institutional changes could improve the efficiency of Chinese agriculture by drawing down labor in the sector.

Rahman (2003) examines the profit efficiency (technical and allocative) of 380 rice farms in Bangladesh using cross-sectional data. He also incorporates the exogenous factors influencing profit efficiency directly in the profit function, which offers more precise and consistent estimates of the parameters than a two-step procedure. He finds that on average farmers can increase profits by 30 percent by improving technical and allocative efficiency. Furthermore, education, experience of growing rice, soil fertility, and agricultural extension have a positive effect on efficiency, while tenure status (rented land versus owner operated), lack of infrastructure, and percentage of non-farm income adversely impact efficiency.

Magalhães et al. (2011) analyze the sources of technical and allocative inefficiency in a cross-sectional sample of 308 beneficiaries of a market-assisted land reform program in Brazil (known as Cédula da Terra). They estimate a stochastic production function and incorporate the sources of inefficiency directly into the production function. They find that the beneficiaries rely mainly on the intensive use of labor and land, while other variable inputs were not significant determinants of production. This occurs because of the credit restrictions on this group, which cannot make the necessary investments that would modify the production structure. Producers who had access to better technical assistance had lower technical and allocative inefficiency. Moreover, education (through its effect on technical assistance and allowing better access to credit) plays a vital role in decreasing inefficiency. The authors conclude that access to land itself does not increase efficiency and productivity because farmers still face many other constraints.

Dinar et al. (2007) use a non-neutral stochastic production function to evaluate the impact of agricultural extension services on the performance of a sample of farms in Crete, Greece.[5] Their approach allows them to examine agricultural extension through its role as an input in production (direct effect) and as a parameter affecting technical efficiency (indirect effect). Their results show that for a 1 percent increase in extension visits, the increase in output through the direct effect dominates the increase through the indirect effect. Therefore, the effect of extension services would be underestimated in a model that incorporates the effect solely through the efficiency parameter. The authors

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[5] In a non-neutral stochastic frontier, the exogenous factors influencing efficiency can be interacted with the inputs. Hence, shifts in the frontier can occur through the impact of inefficiency on input-use.

conclude that extension services should be viewed as a specific type of input in production, and its provision and timing should be adapted according to the socio-demographic characteristics of individual farmers.

Alene and Hassan (2006) estimate stochastic production and cost functions for traditional and hybrid maize producers in eastern Ethiopia. They decompose efficiency into its technical and allocative components while accounting for scale effects. Their results show that conventional decomposition approaches (without accounting for scale effects) overestimate the efficiency measures under increasing returns to scale and underestimate the measures under decreasing returns to scale. Under the conventional approach, traditional maize production comes out to be significantly inefficient, compared to hybrid maize production. When accounting for scale effects, the results reveal that hybrid maize production has greater technical and allocative inefficiency.

The studies reviewed above suggest that technical efficiency varies with household characteristics and the impact of these characteristics differs across regions. Moreover, many of the studies do not account for allocative efficiency in an econometrically consistent manner and have not explored the sources of allocative inefficiency. Using the theory of profit maximization, I include both technical and allocative efficiency in my model and compare them across a set of farm-specific factors.

1.3 Modeling Allocative Inefficiency in a Profit Maximization Framework

I assume that farmers maximize profit defined over aggregate output and multiple inputs. Technical inefficiency is treated as a producer-specific fixed effect, and allocative inefficiency as a producer- and input-specific fixed-effect.[6] Since the two period panel dataset used to estimate the model only spans three years, I find it reasonable to treat technical inefficiency and allocative inefficiency as fixed effects. Treating inefficiency as time-invariant allows us to estimate the model without making strong distributional assumptions about the inefficiency terms. One drawback of this approach is that the technical inefficiency term will subsume any unobserved time-invariant heterogeneity (Greene 2008). Nonetheless, avoiding strong distributional assumptions about the inefficiency terms is an attractive feature of the model.

I follow Kumbhakar and Lovell (2000), and Kumbhakar and Wang (2006) in deriving a primal profit system. The stochastic production function for a single aggregate output is given by:

$$y_{it} = f(x_{it}, z_{it}) \exp\{v_{it} - u_i\} \quad i = 1, \dots, I \tag{1.1}$$

where i and t refer to producers and time, x_{it} is a vector of variable inputs, z_{it} is a vector of quasi-fixed inputs, v_{it} is statistical noise, and u_i is output-oriented and time-invariant technical inefficiency (the percentage loss in output due to technical inefficiency).

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[6] This implies that both technical inefficiency and allocative inefficiency are invariant across time.

The first-order conditions for profit maximization imply:[7]

$$f_n \exp\{v_{it} - u_i\} = \frac{w_{nit}}{p_{it}} \exp\{-\xi_{ni}\} \quad n = 1, \ldots, N \tag{1.2}$$

where p_{it} is the output price and w_{nit} is the price of the nth input, and ξ_{ni} is defined as time-invariant allocative inefficiency. Allocative inefficiency is defined as the extent to which the first-order condition of profit maximization for the jth input fails to hold.

I employ a translog production function which, after dropping the producer subscript i (for convenience), is given by:

$$lny_t =$$

$$\beta_0 + \sum_n \beta_n lnx_{nt} + \sum_q \gamma_q lnz_{qt} + \frac{1}{2}[\sum_n \sum_k \beta_{nk} lnx_{nt} lnx_{kt}] + \frac{1}{2}\left[\sum_q \sum_r \gamma_{qrt} lnz_{qt} lnz_{rt}\right] +$$

$$\sum_n \sum_q \delta_{nq} lnx_{nt} lnz_{qt} + v_t - u \tag{1.3}$$

Using equations (1.2) and (1.3), I derive the input demand equations in (1.4). Since the production function is translog, the input demand equations in (1.4) are not in closed form.

$$lnx_{nt} = lny_{t|v=0} - ln\frac{w_{nt}}{p_t} + \ln\left[\beta_n + \sum_k \beta_{nk} lnx_{kt} + \sum_q \delta_{nq} lnz_{qt}\right] + \xi_n \tag{1.4}$$

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[7] $Max[py - w'x]\ st. y = f(x) \exp\{v - u\}$

I eliminate the time invariant terms β_0, u, and ξ_n by first differencing equations (1.3) and (1.4). After adding a stochastic noise term to each of the input demand equations, the system of equations can be estimated using iterated nonlinear seemingly unrelated regressions (INLSUR).

After estimating the parameters, the intercept β_0 can be calculated using the following normalization:

$$\widehat{\beta_0} = \max(\bar{e}) \tag{1.5}$$

where the $\bar{e}$ is the temporal mean of the residuals of equation (1.3).

After calculating $\widehat{\beta_0}$, I follow Kumbhakar and Lovell (2000) in calculating technical and allocative inefficiency by means of:

$$\hat{u} = \widehat{\beta_0} - \bar{e} \tag{1.6}$$

$$\widehat{\xi_n} = \overline{lnx_{nt}} - \overline{lny_{t|v=0}} + \overline{ln\frac{w_{nt}}{p_t}} - \overline{\ln\left[\beta_n + \sum_k \beta_{nk} lnx_{kt} + \sum_q \delta_{nq} lnz_{qt}\right]} \tag{1.7}$$

where a bar over a term represents its temporal mean.

Values of technical efficiency (1.6) and allocative efficiency (1.7) are producer specific and averaged over time, which makes them time invariant.

1.4 Data Sources and Descriptive Statistics

This section begins with a discussion of the two datasets that are used in the analysis – Pakistan Rural Household Survey I (PRHS-I) and Pakistan Rural Household Survey II (PRHS-II). Section 1.4.2 then presents a descriptive analysis of tenancy, farm size and irrigation water in Pakistan.

1.4.1 The PRHS-I and PRHS-II Surveys

PRHS-I is a nationally representative survey that includes data from 2,600 households in 143 villages across the four provinces of the country (Punjab, Sindh, Khyber Pakhtunkhwa – KP, and Balochistan). About 50 percent of the households in PRHS-I owned or operated farmland. PRHS-II followed a sample of 1,800 households from 94 villages, some of which also were included in PRHS-I. However, the PRHS-II households were sampled only from the Punjab and Sindh provinces. About 60 percent of the households in PRHS-II owned or operated farmland.

The surveys aimed at collecting data from rural households to allow an analysis of Pakistan’s rural economy. Households in PRHS-I were surveyed from September 2001 to January 2002. Agricultural households were asked information about their agricultural activities in the 2000 kharif (autumn harvest) and 2001 rabi (spring harvest) seasons. Households in PRHS-II were surveyed from August 2004 to October 2004, and agricultural households provided information on the 2003 kharif and 2004 rabi seasons. The two datasets contain plot-level information on agricultural production, tenure and irrigation water availability as well as household-level socioeconomic data. Although some households are observed over time, the plots are not uniquely identified across the surveys.

Panel estimation of the allocative inefficiency of groundwater was restricted to farms in Punjab and Sindh because these were the only two provinces included in both waves of the PRHS survey. Therefore, the descriptive analysis in the following section focuses only on observations from Punjab and Sindh in the two PRHS waves. An earlier analysis of the agrarian structure of Pakistan using both the waves showed that the agrarian structure of Punjab and Sindh differs considerably from the agrarian structure of KP and Balochistan. The results for canal water and groundwater availability showed that more than 85 percent of plots in Punjab and Sindh in both time periods receive either canal water, groundwater, or both. In KP and Balochistan almost 60 percent of plots neither receive canal water nor groundwater. Therefore, even if there were panel data for these provinces, KP and Balochistan would probably require a separate study of the efficiency of irrigation water. Given that Punjab and Sindh account for 66 percent and 18 percent, respectively, of total cropped area in the country (Agricultural Census 2010), my sample covers nearly 85 percent of cultivated area in Pakistan.

1.4.2 Descriptive Statistics of the Two PRHS Surveys

Agrarian Structure

This section provides a description of tenancy and irrigation water availability at the level of households and plots across Punjab and Sindh provinces in the PRHS waves. Additional statistics on the agrarian structure across Punjab, Sindh, KP and Balochistan are provided in Appendix A.

Tenancy

Since independence, Pakistan has seen a rise in owner-cultivation and a steady decline in tenant farming, especially sharecropping (Cheema and Nasir 2010). Table 1.1 shows the share of plots under owner-cultivation and the share of plots leased-in under fixed-rent tenancy and under sharecropping. I examine the status of all plots in the dataset that are farmed, including plots of landless households who only lease-in, as well as plots of owners who also might choose to lease-in. I report the shares by season in order to investigate potentially important differences.

Results in Table 1.1 show that the majority of the plots were owner-cultivated in both the kharif and rabi seasons. Based on PRHS-I, owner-cultivated plots in Punjab and Sindh accounted for 57 percent of the total in the kharif season, and 59 percent in the rabi season. Table 1.1 also shows that owner-cultivation of plots is slightly more common in the rabi season. The share of plots leased-in by sharecroppers was almost three times the share of plots leased-in by fixed-rent tenants in both seasons and periods.

The share of owner-cultivated plots remained relatively constant over time (between the two PRHS waves), rising by 2.4 percentage points in the kharif season and by 1 percentage point in the rabi season. Leasing-in by fixed-rent tenants increased between 1 and 2 percentage points, while a decline in the importance of sharecropping is observed over time. Sharecropped plots fall between 2 and 5 percentage points, depending on the season, to less than 30 percent of cultivated plots. This is consistent with the long-term national trend.

Table 1.1: Share of Plots by Tenure Classification (Owner-Cultivated and Leased-In Plots)

	PRHS-I	PRHS-II
Kharif		
Owner-Cultivated	57.1	59.5
Leased-In by Fixed-Rent Tenants	8.5	10.8
Leased-In by Sharecroppers	34.4	29.7
Number of Plots	1591	1583
Rabi		
Owner-Cultivated	59.2	60.2
Leased-In by Fixed-Rent Tenants	9.4	10.8
Leased-In by Sharecroppers	31.4	29.0
Number of Plots	1,578	1,563

Area and Farm Size by Tenure Status

The above description shows that owner-cultivation is the predominant form of tenancy in terms of the share of plots farmed in Pakistan. The same conclusion is reached when area shares are analyzed. Table 1.2, which is based on owner-cultivated and leased-in plots, shows that the share of total area under owner-cultivation is almost double the share under sharecropping. The area under fixed-rent tenancy is less than 11 percent of total area. Over time, the area under owner-cultivation increases while the area under sharecropping falls.

Table 1.2: Share of Area Operated by Tenure (percent)

	PRHS-I	PRHS-II
Owner-Cultivated	57.8	66
Fixed-Rent	10.9	10
Sharecropped	31.2	24
Total	100	100

The area under owner-cultivated exceeds that under fixed-rent tenancy, and the area under sharecropping reflects the combination of the number of farms under each form of tenure and average farm size. Table 1.3 reports descriptive statistics on plot size by tenure for owner-cultivated and leased-in plots. The results show that fixed-rent plots had the same median area as sharecropped plots, which was higher than the area of owner-cultivated plots. Fixed-rent tenants had the largest mean plot size, followed by owner-cultivators. Over time, there was little change in the median area of sharecropped and fixed-rent plots, while the median plot area of owner-cultivated increased by 2 kanals.[8]

Table 1.3: Plot Size by Tenure Status (Kanals)

PRHS-I				
	Mean	Median	Standard Deviation	Number of Plots
Owner-Cultivated	35.0	18.0	59.9	1064
Leased-In by Fixed-Rent Tenants	45.1	24.1	62.7	156
Leased-In by Sharecroppers	34.0	24.0	26.4	598
PRHS-II				
	Mean	Median	Standard Deviation	Number of Plots
Owner-Cultivated	34.3	20.0	47.6	915
Leased-In by Fixed-Rent Tenants	43.9	24.0	115.8	180
Leased-In by Sharecroppers	31.0	24.0	25.6	490

Irrigation Water Availability

In this section, I examine the irrigation water supply characteristics of the plots in Punjab and Sindh in the PRHS samples. This comparison allows us to determine whether I have a large enough sample of irrigated plots in order to conduct a thorough analysis of water-use inefficiency, and to describe their main characteristics. The analysis includes both leased-out and leased-in plots.

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[8] 8 kanals equals 1 acre or 0.405 hectares.

Canal Irrigation

In the PRHS datasets, households were asked whether their plots receive canal irrigation in both kharif and rabi, in one season only, or whether their plots do not receive canal irrigation. Table 1.4 presents the distribution of plots with respect to canal irrigation.

Table 1.4: Share of Plots that Receive Canal Irrigation (percent)

Canal Irrigation	PRHS-I	PRHS-II
Kharif Only	24.0	33.2
Rabi Only	1.6	0.1
Kharif and Rabi	41.7	39.4
No Canal Irrigation	32.8	27.3
Number of Plots	2,355	1,917

The majority of plots in Punjab and Sindh received canal irrigation in both kharif and rabi. In the second period (PRHS-II) the share of plots that received canal irrigation in both seasons fell slightly, but so did the share of plots that did not receive canal irrigation at all. The share of plots that received canal irrigation in kharif rose by 9 percentage points in the second period.

The PRHS datasets do not distinguish between plots that did not have access to canal water and plots that might have had access to canal water but were not irrigated with it. To get a better understanding of plots with access to canal water Table 1.5 reports the location of the plots on a watercourse.

Table 1.5: Share of Plots by Location on Watercourse (percent)

Location	PRHS-I	PRHS-II
Head	17.1	23.0
Middle	37.7	33.8
Tail	45.2	43.1
Number of Plots	1,569	1,393

Table 1.5 shows that nearly 45 percent of the plots in Punjab and Sindh in the first period were located at the tail of the watercourse. Over the two PRHS waves, the share of plots located at the tail decreased slightly, and the share of plots located at the head increased. It is not clear if this reflects an improvement in the irrigation system or is a reflection of a change in the sample. Not shown in Table 1.5 is the fact that 786 plots (33 percent) in PRHS-I and 524 plots (27 percent) in PRHS-II did not lie on a watercourse. These plots most likely rely on groundwater irrigation, which I will address later.

Location on the watercourse does not necessarily guarantee access to canal water. To examine the relationship between canal irrigation and the location of plots on the watercourse I cross-tabulate the two variables for Punjab and Sindh in Table 1.6 below. Table 1.6 shows that the share of plots located on the watercourse that did not receive canal irrigation dropped from 0.8 percent to 0 percent over time. Thus, in these provinces location on the watercourse did guarantee access to canal irrigation. Not shown in Table 1.6 is that almost all plots that are not located on the watercourse did not receive canal irrigation.

Table 1.6: Location on Watercourse of Plots that Receive Canal Irrigation (percent)

PRHS-I

	Location on Watercourse			
Canal Irrigation	Head	Middle	Tail	Total
Kharif Only	4.5	12.4	18.3	35.3
Rabi Only	0.3	0.7	1.4	2.4
Kharif and Rabi	12.2	24.2	25.2	61.6
No Canal Irrigation	0.1	0.4	0.3	0.8
Total	17.0	37.8	45.2	100

Based on 1,568 plots

PRHS-II

	Location on Watercourse			
Canal Irrigation	Head	Middle	Tail	Total
Kharif Only	9.1	13.7	22.9	45.7
Rabi Only	0.1	0.1	0.0	0.1
Kharif and Rabi	13.9	20.0	20.2	54.2
No Canal Irrigation	0.0	0.0	0.0	0.0
Total	23.0	33.8	43.1	100

Based on 1,393 plots

Since most plots located on the watercourse received canal irrigation, I can conclude that location on the watercourse mostly guarantees access to canal water. However, as expected, location on the watercourse influences the reliability of access to irrigation water. For example, plots located at the head were almost 30 percent more likely to have irrigation water in both seasons, relative to plots at the tail. The advantage, relative to plots in the middle of the course, declined from 11 percent to 2 percent over the two PRHS waves. Of relevance to my study of allocative efficiency, the above analysis shows that plots located on the watercourse would be either fully or partially canal irrigated.

Nearly one-third of the plots in Punjab and Sindh in the two periods were neither on the watercourse nor received canal irrigation. These plots might have been supplied with groundwater.

Groundwater Availability

In the PRHS datasets, groundwater availability on plots is differentiated by quality of groundwater. Table 1.7 reports the share of plots that had different qualities of groundwater and the share of plots that did not have groundwater irrigation.

Table 1.7: Share of Plots with Groundwater Irrigation (percent)

Groundwater Irrigation	PRHS-I	PRHS-II
Good-Quality Groundwater	40.0	37.2
Medium-Quality Groundwater	11.0	8.7
Poor-Quality Groundwater	8.6	3.4
No Tubewell Irrigation	40.4	50.8
Number of Plots	2,256	1,917

A large share of the plots in Punjab and Sindh in both periods did not use groundwater for irrigation. The share of plots that did not use groundwater for irrigation increased from 40.4 percent to 50.8 percent over time. In both periods, groundwater-irrigated plots generally received good-quality water. Plots that did not use groundwater for irrigation might rely on canal water for irrigation instead. I examine this possibility in the subsequent tables.

Groundwater use might depend on the location of plots on the watercourse. In Table 1.8, I provide cross-tabs of groundwater availability and the location of plots on the watercourse.

Table 1.8: Location on Watercourse of Plots that Use Groundwater Irrigation (percent)

PRHS-I

	Location on Watercourse			
Groundwater Irrigation	Head	Middle	Tail	Total
Good-Quality Groundwater	5.3	13.9	17.7	36.9
Medium-Quality Groundwater	1.6	5.4	6.9	13.9
Poor-Quality Groundwater	1.6	5.5	4.8	11.9
No Tubewell Irrigation	8.7	12.9	15.8	37.3
Total	17.2	37.7	45.1	100

Based on 1,560 plots

PRHS-II

	Location on Watercourse			
Groundwater Irrigation	Head	Middle	Tail	Total
Good-Quality Groundwater	6.6	11.8	14.3	32.7
Medium-Quality Groundwater	2.3	4.1	2.5	8.9
Poor-Quality Groundwater	0.7	1.1	2.2	4.0
No Tubewell Irrigation	13.5	16.9	24.1	54.5
Total	23.0	33.8	43.1	100

Based on 1,393 plots

Plots that were located at the head of the watercourse, and thus had better access to canal irrigation, were less likely to utilize groundwater for irrigation. Interestingly, they were also less likely to have good-quality groundwater irrigation. In the first period, for example, plots with no tubewell for irrigation fell from 50 percent at the head to 35 percent at the tail of the watercourse. In the same period, plots with good-quality groundwater rose from 31 percent at the head to 39 percent at the tail. The differences in both use and quality became less pronounced over time.

I mentioned previously that households with plots that receive canal water might choose not to use groundwater, and those that don't have access to canal water would be more likely to use groundwater. Therefore, I now provide cross-tabs on canal water availability with groundwater use in Table 1.9 below. Unlike in Table 1.8, the data now include plots that are not located on a watercourse.

Table 1.9 shows that most plots in the Punjab and Sindh have access to canal water, groundwater, or both. In the first period, for example, 43 percent of plots had canal water in both seasons, about 70 percent had it in at least one season, 60 percent had tubewell irrigation, and 86 percent had both types of irrigation. According to PRHS-II, the percentage of plots with canal irrigation in at least one season rose to 73 percent, tubewell irrigation fell to 49 percent, and with one or the other it rose to 89 percent. The pattern of changes highlights the substitutability of the water sources. Because more than 85 percent of plots used irrigation in one form or another, the analysis of allocative efficiency of irrigation water will cover the overwhelming majority of plots in Punjab and Sindh.

Table 1.9: Share of Plots that Use Canal and Groundwater Irrigation (percent)

PRHS-I

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	14.3	2.7	3.5	4.3	24.8
Rabi Only	0.4	0.2	0.4	0.6	1.6
Kharif and Rabi	10.6	6.9	4.4	21.3	43.2
No Canal Irrigation	14.7	1.2	0.4	14.2	30.4
Total	40.0	11.0	8.7	40.4	100

Based on 2,255 plots

PRHS-II

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	14.5	1.2	0.9	16.6	33.2
Rabi Only	0.1	0.1	0.0	0.0	0.1
Kharif and Rabi	9.2	5.3	2.0	23.0	39.4
No Canal Irrigation	13.5	2.2	0.5	11.2	27.3
Total	37.2	8.7	3.4	50.8	100

Based on 1,917 plots

The analysis in this section suggests that in Punjab and Sindh a substantial number of plots use canal water and/or groundwater irrigation. Although a large share of the plots is canal-irrigated only, there is a significant share of plots that utilize both canal water and groundwater irrigation.

The preliminary analysis of the PRHS datasets presented in this section shows that tenancy and water characteristics in Punjab and Sindh have not changed substantially in the short time that elapsed between the two waves of the PRHS. This suggests that many households are likely to be cultivating the same plots over time. Unfortunately, the structure of the PRHS panel dataset does not permit us to identify plots uniquely over time. For this reason, the econometric analysis presented in Section 1.6 is conducted at the household level. The above findings and the structure of the two PRHS waves lead us to the creation of the panel dataset at the household level, as explained in the next section. I use this panel dataset to estimate the allocative inefficiency of water.

1.5 The Panel Dataset

In order to form a panel dataset of agricultural households, I aggregated plot level information on agricultural production, tenure, and plot characteristics up to the household level. PRHS-I includes 1,316 agricultural households from the Punjab and Sindh provinces. PRHS-II was restricted to the same two provinces, and includes 1,035 households from PRHS-I and an additional 108 agricultural households that were not observed in PRHS-I.

I constructed the panel by including households that appeared in the same season in both waves of the survey and produced at least one of the five main crops: wheat, IRRI-rice, basmati rice, cotton, and sugarcane. These crops comprise more than 80 percent of total cultivated area in the provinces. IRRI-rice, basmati rice, cotton, and sugarcane are kharif crops, while wheat is a rabi crop. There were 636 households observed in kharif (2000) and kharif (2003), and 547 households observed in rabi (2001) and rabi (2004). I pooled the observations for the two seasons. Around 170 households dropped out of the analysis, due to missing observations on tenure and other key variables. After obtaining the initial estimation results, a small group of additional households were also removed from the sample because their level of technical efficiency was discretely higher than the remaining households, suggesting either considerable measurement error or that they were operating with a different technology. The final sample used for the estimation included 1,900 observations drawn from 492 kharif households and 458 rabi households observed in each period.

Table 1.10 presents the structure of PRHS-I and PRHS-II for included households that appear in both waves and either own or operate agricultural land. The table shows data on both leased-in and leased-out plots.[9] The data indicate that the geographical distributions of both households and plots are similar across the two survey waves. Households and plots in Punjab represent 53 percent and 56 percent of the total in PRHS-II, and when restricting PRHS-I to only include Punjab and Sindh, households and plots in Punjab account for 53 percent and 57 percent.

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[9] Thus, some plots might be counted twice here. In my analysis, I use leased-in plots since information on agricultural production is collected from owner-cultivators and tenants who lease-in land.

Table 1.10: Structure of the PRHS Dataset (households and percent of total)

	Punjab	Sindh	Punjab and Sindh
PRHS-I			
Number of agricultural households	694 (37)	622 (33)	1,316 (70)[10]
Number of plots	1,350 (38)	1,007 (29)	2,357 (67)[11]
PRHS-II			
Number of agricultural households	608 (53)	535 (47)	1,143 (100)
Number of plots	1,078 (56)	839 (44)	1,917 (100)
Number of Households Included in the Panel Estimation			
	Punjab	Sindh	Punjab and Sindh
Kharif	209 (42)	283 (58)	492 (100)
Rabi	342 (75)	116 (25)	458 (100)

Note: Total observations included in the panel estimation: 1,900.
Data in parentheses shows households in provinces as a percentage of the total in each survey.

1.5.1 Empirical Specification and Construction of Variables

Because the production function in my model is defined over a single output, I had to aggregate the output of several crops for each household. I created separate output quantity indices for the kharif and rabi crops, since I differentiated households by season. The output quantity indices included the five main crops and several minor crops. The minor kharif crops are: maize, sorghum, groundnuts, sesamum, and chilies, while the minor rabi crops are: barley, rapeseed, sunflower seed, potato, onion, tomato, peas, and

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[10] Of the 1,316 households in Punjab and Sindh, 53 percent are in Punjab and 47 percent are in Sindh.

[11] Of the 2,357 plots in Punjab and Sindh, 57 percent are in Punjab and 43 percent are in Sindh.

spices. I used The Elteto-Koves-Schultz (EKS) method to construct the quantity index. The advantage of this method is that it controls for spatial variation in prices. The approach involved calculating a matrix of Fisher Price Indices using the prices of these crops in each community as a base. I then took the geometric average of the calculated Fisher Price Indices to construct the EKS Fisher Price Index. I generated the output quantity index by dividing the total revenue from all the crops by the EKS Fisher Price Index. I deflated the prices in PRHS-II to the PRHS-I survey period.[12]

I use three variable inputs: hired labor, fertilizer, and groundwater. Own male labor, own female labor, capital and surface water are treated as quasi-fixed inputs. Both variable and quasi-fixed inputs were normalized by total cropped area (Ha). This normalization allows us to exclude land as an input in the production function and keeps the number of estimated parameters within a reasonable limit.

PRHS-I only has information on the cost of hired labor. PRHS-II has data on the number of days of both male and female hired labor. To get a measure of the quantity of hired labor for households in PRHS-I, I divided the cost of hired labor by a weighted average of the community-level male and female wage rates. I calculated the weights from the ratio of the number of days of male-hired labor and the number of days of female-hired labor in PRHS-II. Since I cannot disaggregate the quantity of hired labor by gender in PRHS-I, I constructed a quantity index of aggregate hired labor in PRHS-II. I first constructed an index of male and female wage rates using the EKS method and then divided the total cost of hired labor by the EKS Fisher Price Index. I used the same

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[12] I obtained the GDP deflator from State Bank of Pakistan's *Handbook of Statistics on Pakistan Economy 2010*.

method to construct fertilizer and capital quantity indices. Fertilizer includes di-ammonium phosphate (DAP), urea, and manure, while capital includes the hours of tractor and thresher/harvester use.

Groundwater is measured in hours. The power of tubewells pumps affects the rate of groundwater extraction. In Pakistan, 90 percent of farmers extract groundwater using 16- to 20-horsepower Chinese tubewell pumps (Qureshi 2012). Since I do not have information on the type of tubewell pumps used by each farmer, I assume that they used the 16- to 20-horsepower Chinese tubewells. Hence, I measure the quantity of groundwater with some error. The Chinese pumps extract groundwater at a rate of 1 cubic foot per second. I could use this extraction rate to convert the number of hours of pump use into cubic feet of groundwater applied. Since I assume all farmers use the same type of tubewell, no information is lost by keeping the quantity of groundwater as hours. The price of groundwater is in rupees per hour.

Farmers in Pakistan have fixed surface-water allocations per unit of land. Thus, I cannot treat surface water as a variable input. Therefore, I cannot estimate the allocative inefficiency of surface water within the current framework. Moreover, both PRHS-I and PRHS-II do not have information on the quantity of surface water applied by farmers. In my analysis, I include the cost of surface water as an input. The normalization of the cost of surface water by total cropped area provides a reasonable measure of the quantity of surface water, since surface-water allocations to farms in Pakistan depend on farm size (allocation is fixed per unit of land).

As mentioned earlier, the econometric analysis is conducted at the household-level. To control for time varying heterogeneity at the plot-level, I include the shares of environmental and locational characteristics of plots in total household farm area. These include the share of total farm area with access to canal water, the share of total farm area at the head, middle and tail of a watercourse, and the share of total farm area that receives good-, medium-, and poor-quality groundwater.

I first estimate a model with the households observed in each season pooled together. I differentiate seasons by the intercept only. To control for differences in the model parameters across seasons, I would have to include an interaction of a season dummy with all the linear and second-order variables in the translog production function. This would considerably inflate the number of parameters in the model and decrease the degrees of freedom. Moreover, with a system of equations a significant increase in the number of parameters would increase the computational burden of the estimation process. Because elasticities are not constant when using a translog, and depend on the values of the inputs, separate elasticities and levels of technical and allocative inefficiency can be calculated by season. As an alternative, I also estimate the model for each season separately.

1.5.2 Description of Variables Used in the Econometric Model

Table 1.11 provides summary statistics of output, variable inputs, quasi-fixed inputs, and control variables across the kharif and rabi seasons in periods 1 and 2. In the table, I have normalized the output quantity index by the mean output index price in each season and period to get a measure of crop revenue per hectare across each season and period. I also report hired labor in number of days so that it can be compared with own farm labor. I divided the total expenditure on hired labor by a weighted average of male and female wage rates to get hired labor in days. These normalizations facilitate interpretation, but do not affect the econometric estimates.

Table 1.11 shows that the median output per hectare in kharif increased about 17 percent across the two periods. The median values of all inputs, except capital and surface water, are higher in kharif (2003) relative to kharif (2000). The water and tenure variables change very little in the kharif season across the two periods. The median output per hectare in rabi (2004) is about 11 percent higher than in rabi (2001). The median value of surface water in rabi (2004) is considerably higher than in rabi (2001), but the mean value is only slightly higher. The mean and median values of fertilizer in rabi drop slightly over time. The mean and median values of water and tenure variables in rabi are similar across the two periods.

In both periods, the mean value of the hours of groundwater per hectare is higher in kharif than in rabi, but the median value in kharif is zero. This suggests that the share of households that use groundwater is greater in rabi, but that households use more hours of groundwater per hectare in kharif than in rabi. The water variables show that the share of total area that receives groundwater of any quality is greater in rabi than in kharif. The mean and median values of surface water are higher in kharif than in rabi across both periods. Since surface water is highly limited in rabi, a larger proportion of farmers supplement surface water with groundwater in rabi. The share of total area that receives canal irrigation is also higher in kharif than in rabi. Farmers grow wheat (a low water intensity crop) in rabi and cotton, rice, and sugarcane (high water intensity crops) in kharif and, hence, their use of surface water per hectare is higher in kharif than in rabi.

Own male labor is the dominant form of labor across both periods and seasons. The mean level of hired labor is slightly higher in kharif. Since households grow labor-intensive crops in kharif, they supplement their own labor with hired labor. The mean level of own female labor is only slightly higher than the mean level of hired labor across seasons.

All of the inputs in the sample contain at least some zero values. To account for the zero values in the translog production function, I follow Battese and Broca (1997) by adding a dummy variable λ_n in the production function and transforming lnx_n to lnx_n^* where:

$$\lambda_n = \begin{cases} 0 \; if \; x_n = 0 \\ 1 \; if \; x_n > 0 \end{cases} \text{ and } x_n^* = ArgMax(x_n, 1 - \lambda_n)$$

The above transformation implies that when the input x_n is applied, $x_n^* = x_n$, but when x_n is not applied $x_n^* = 1$. The inclusion of λ_n signifies that the intercept term differs between farmers that apply the input and farmers that do not apply the input.

Table 1.11: Summary Statistics of the Variables in the Stochastic Profit System

Kharif 2000	Mean	Median	St. Dev.	Min	Max
Output, Variable Inputs and Quasi-fixed Inputs					
Output (index Rs./ha)	19,928.42	18,049.48	12,203.83	131.18	72,124.73
Hired Labor (days)	10.36	0.00	21.10	0.00	205.42
Fertilizer (index Rs./ha)	4,047.45	2,858.32	4,899.69	0.00	52,476.20
Groundwater (hours/ha)	61.25	0.00	135.35	0.00	1,731.47
Own Male Labor (days/ha)	71.86	28.71	113.45	0.00	864.87
Own Female Labor (days/ha)	13.89	0.00	41.79	0.00	593.05
Capital (index Rs./ha)	3,308.90	2,320.84	3,682.35	0.00	41,615.92
Surface Water (Rs./ha)	308.71	200.77	510.71	0.00	7,413.16
Water Variables					
Surface Water (percent area)	85.11	100.00	35.24	0.00	100.00
Head of Watercourse (percent area)	16.75	0.00	35.58	0.00	100.00
Middle of Watercourse (percent area)	29.78	0.00	43.43	0.00	100.00
Tail of Watercourse (percent area)	40.09	0.00	46.64	0.00	100.00
Good-Quality Groundwater (percent area)	46.47	0.00	49.63	0.00	100.00
Medium-Quality Groundwater (percent area)	10.20	0.00	29.98	0.00	100.00
Poor-Quality Groundwater (percent area)	11.40	0.00	31.65	0.00	100.00
Tenure Variables[13]					
Owner-Cultivated (percent area)	57.55	100.00	46.51	0.00	100.00
Fixed-Rent (percent area)	6.63	0.00	21.08	0.00	100.00
Sharecropped (percent area)	35.81	0.00	46.51	0.00	100.00

Descriptive statistics calculated from 466 observations.

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[13] The tenure variables were not included in the estimation because they have very little variation over time. Since I later compare the technical efficiency and allocative efficiency estimates across tenure, I present the descriptive statistics on these variables in the table.

Kharif 2003

	Mean	Median	St. Dev.	Min	Max
Output, Variable Inputs and Quasi-fixed Inputs					
Output (index Rs./ha)	27,605.41	21,110.62	21,812.67	693.14	193,819.40
Hired Labor (days)	14.58	4.88	24.33	0.00	202.63
Fertilizer (index Rs./ha)	4,352.80	3,214.51	4,740.71	0.00	57,719.08
Groundwater (hours/ha)	71.36	0.00	167.03	0.00	1,593.64
Own Male Labor (days/ha)	64.41	44.48	68.84	0.00	590.09
Own Female Labor (days/ha)	17.53	6.18	29.34	0.00	261.93
Capital (index Rs./ha)	3,808.48	2,109.69	8,895.50	0.00	162,576.80
Surface Water (Rs./ha)	242.53	98.84	370.59	0.00	3,294.74
Water Variables					
Surface Water (percent area)	84.66	100.00	35.93	0.00	100.00
Head of Watercourse (percent area)	17.96	0.00	37.08	0.00	100.00
Middle of Watercourse (percent area)	29.35	0.00	43.81	0.00	100.00
Tail of Watercourse (percent area)	37.56	0.00	46.89	0.00	100.00
Good-Quality Groundwater (percent area)	42.42	0.00	49.24	0.00	100.00
Medium-Quality Groundwater (percent area)	7.73	0.00	26.60	0.00	100.00
Poor-Quality Groundwater (percent area)	3.22	0.00	17.67	0.00	100.00
Tenure Variables					
Owner-Cultivated (percent area)	55.45	100.00	47.40	0.00	100.00
Fixed-Rent (percent area)	9.50	0.00	26.75	0.00	100.00
Sharecropped (percent area)	35.05	0.00	46.40	0.00	100.00

Descriptive statistics calculated from 466 observations.

Rabi 2001

	Mean	Median	St. Dev.	Min	Max
Output, Variable Inputs and Quasi-fixed Inputs					
Output (index Rs./ha)	17,202.39	16,498.57	11,439.18	328.16	113,547.10
Hired Labor (days)	7.27	0.00	18.30	0.00	254.99
Fertilizer (index Rs./ha)	4,561.10	3,527.96	6,190.17	0.00	103,274.20
Groundwater (hours/ha)	36.16	29.65	45.68	0.00	370.66
Own Male Labor (days/ha)	66.01	31.30	95.65	0.00	790.74
Own Female Labor (days/ha)	14.26	1.10	38.12	0.00	370.66
Capital (index Rs./ha)	3,262.66	2,784.13	2,101.54	0.00	21,294.75
Surface Water (Rs./ha)	177.10	8.90	268.67	0.00	2,223.95
Water Variables					
Surface Water (percent area)	39.44	0.00	48.70	0.00	100.00
Head of Watercourse (percent area)	9.33	0.00	27.71	0.00	100.00
Middle of Watercourse (percent area)	25.68	0.00	42.17	0.00	100.00
Tail of Watercourse (percent area)	29.97	0.00	44.05	0.00	100.00
Good-Quality Groundwater (percent area)	54.51	100.00	49.44	0.00	100.00
Medium-Quality Groundwater (percent area)	13.69	0.00	34.18	0.00	100.00
Poor-Quality Groundwater (percent area)	5.66	0.00	23.03	0.00	100.00
Tenure Variables					
Owner-Cultivated (percent area)	65.78	100.00	43.95	0.00	100.00
Fixed-Rent (percent area)	8.55	0.00	24.14	0.00	100.00
Sharecropped (percent area)	25.67	0.00	42.00	0.00	100.00

Descriptive statistics calculated from 469 observations.

Rabi 2004

	Mean	Median	St. Dev.	Min	Max
Output, Variable Inputs and Quasi-fixed Inputs					
Output (index Rs./ha)	21,735.97	18,251.73	14,421.25	1,372.55	140,782.20
Hired Labor (days)	7.35	0.00	18.77	0.00	197.68
Fertilizer (index Rs./ha)	3,760.11	3,323.59	2,926.60	0.00	23,300.35
Groundwater (hours/ha)	47.21	24.71	110.40	0.00	1,976.84
Own Male Labor (days/ha)	41.64	26.36	53.33	0.00	484.33
Own Female Labor (days/ha)	11.75	2.64	23.43	0.00	204.27
Capital (index Rs./ha)	5,560.94	3,364.77	10,582.67	344.24	140,338.90
Surface Water (Rs./ha)	198.82	70.60	292.38	0.00	1530.46
Water Variables					
Surface Water (percent area)	37.87	0.00	48.45	0.00	100.00
Head of Watercourse (percent area)	13.74	0.00	33.52	0.00	100.00
Middle of Watercourse (percent area)	23.17	0.00	41.21	0.00	100.00
Tail of Watercourse (percent area)	25.69	0.00	42.70	0.00	100.00
Good-Quality Groundwater (percent area)	52.19	100.00	49.97	0.00	100.00
Medium-Quality Groundwater (percent area)	11.35	0.00	31.70	0.00	100.00
Poor-Quality Groundwater (percent area)	4.48	0.00	20.70	0.00	100.00
Tenure Variables					
Owner-Cultivated (percent area)	64.65	100.00	45.00	0.00	100.00
Fixed-Rent (percent area)	12.88	0.00	30.36	0.00	100.00
Sharecropped (percent area)	22.47	0.00	40.58	0.00	100.00

Descriptive statistics calculated from 469 observations.

1.6 Estimation Results

1.6.1 Results from the Pooled Sample

The translog production function contains second-order terms for all inputs. Therefore, the individual parameter estimates can be difficult to interpret. As an alternative, Table 1.12 reports the elasticities of the variable and quasi-fixed inputs for the sample as a whole and across several types of households. The elasticities were calculated at the median values of the inputs for each type of household. The elasticity of output, E_n, with respect to input x_n, is given by:

$$E_n = \beta_n + \sum_k \beta_{nk} ln x_k + \sum_q \delta_{nq} ln z_q \quad For\ each\ n \tag{1.8}$$

In the overall sample, groundwater has the largest percentage impact on output per hectare, followed by fertilizer. A 1 percent increase in groundwater per hectare leads to a 0.18 percent increase in output per hectare. The elasticities of hired labor and own female labor are positive and statistically significant, but the elasticity of hired labor is nearly zero. These elasticities differ significantly across types of households.

The impact of groundwater on output per hectare is significantly larger for owner-cultivators and fixed-rent tenants than for sharecroppers. This is explained by the higher share of farmers in these groups that use groundwater: 67 percent of owner-cultivators and 86 percent of fixed-rent tenants relative to only 24 percent of sharecroppers. The impact of own male labor on output per hectare is negative and significant for owner-cultivators and fixed-rent tenants. This suggests that own male labor is unconstrained on owner-cultivated and fixed-rent farms. However, own female labor has a positive and statistically significant impact on output per hectare on sharecropped plots, which suggests that own female labor is constrained on sharecropped farms.

When elasticities are compared across farm sizes, the impact of hired labor becomes more pronounced. Because the importance of hired labor grows with farm size, this variable has a significantly larger impact on output per hectare on large and medium farms. In contrast, the impact of own female labor is greater on small farms.

Groundwater has a similar impact on output per hectare for small, medium and large farms. Groundwater per hectare also has a significantly larger impact on output per hectare on farms that do not receive surface water relative to farms that receive surface water. This suggests that households that do not receive surface water would, at the margin, benefit considerably from additional groundwater irrigation.

Across seasons, hired labor has a much larger impact on output per hectare in kharif than in rabi. Since households grow labor-intensive crops such as cotton, rice, and sugarcane in kharif, the marginal impact on output per hectare from an increase in hired labor is significantly higher in this season. Groundwater, in contrast, has a substantially larger impact on output per hectare in rabi than in kharif. Since rabi is the dry season and surface water supply is limited, households benefit from increasing the application of groundwater.

These results have important implications because they identify where farmers are most constrained, and provide clues about how policy could most effectively influence the performance of farmers in Pakistani agriculture. Since groundwater and fertilizer have the highest elasticities across most groups, land productivity would benefit from a marginal increase in the use of these inputs. The findings suggest that policies could be designed to help farmers increase the application of fertilizer and groundwater. However, these findings do not address the question of whether farmers produce the maximum possible amount of output per hectare from their inputs. Nor do the findings address the issue of the suboptimal utilization of groundwater, which might require a different set of policies. I turn to these issues in the next subsections.

Table 1.12: Estimated Elasticities of the Variable and Quasi-Fixed Inputs across Household Groups

	Overall
Hired Labor	0.00047^{***}
	(0.00003)
Fertilizer	0.10782^{***}
	(0.01008)
Groundwater	0.17554^{***}
	(0.01108)
Own Male Labor	-0.01710
	(0.01200)
Own Female Labor	0.07404^{*}
	(0.04134)
Capital	-0.01692
	(0.01574)
Surface Water	0.00709
	(0.01141)

	Owner Cultivated	**Fixed-rent**	**Sharecropped**
Hired Labor	0.00045^{***}	0.00044^{***}	0.00053^{***}
	(0.00004)	(0.00004)	(0.00004)
Fertilizer	0.11064^{***}	0.10935^{***}	0.10454^{***}
	(0.01034)	(0.01022)	(0.00978)
Groundwater	0.24946^{***}	0.26402^{***}	0.01110^{***}
	(0.01565)	(0.01656)	(0.00174)
Own Male Labor	-0.03095^{**}	-0.02921^{**}	0.01752
	(0.01328)	(0.01278)	(0.01388)
Own Female Labor	0.08022	0.07948	0.05744^{**}
	(0.05695)	(0.05704)	(0.02414)
Capital	-0.01903	-0.02039	-0.01085
	(0.01750)	(0.01793)	(0.01624)
Surface Water	0.00290	0.00345	0.01470
	(0.01355)	(0.01382)	(0.04067)

	Small Farm (<4 ha)	**Medium Farm (4 to 10 ha)**	**Large Farm (>10 ha)**
Hired Labor	0.00047***	0.30911***	0.32900***
	(0.00003)	(0.01067)	(0.01136)
Fertilizer	0.10812***	0.10640***	0.10770***
	(0.01011)	(0.00995)	(0.01007)
Groundwater	0.18628***	0.09995***	0.22212***
	(0.01174)	(0.00648)	(0.01398)
Own Male Labor	-0.01535	-0.00851	-0.00525
	(0.01260)	(0.01134)	(0.01203)
Own Female Labor	0.07108**	0.07405	0.07441
	(0.03126)	(0.05608)	(0.05615)
Capital	-0.01779	-0.01388	-0.01268
	(0.01544)	(0.01657)	(0.01685)
Surface Water	0.00837	0.00717	0.00892
	(0.01307)	(0.01254)	(0.01329)

	With Surface Water	**Without Surface Water**
Hired Labor	0.00052***	0.00046***
	(0.00004)	(0.00004)
Fertilizer	0.10686***	0.10970***
	(0.00999)	(0.01025)
Groundwater	0.00998***	0.27428***
	(0.00150)	(0.01725)
Own Male Labor	-0.01772	0.00178
	(0.01288)	(0.01409)
Own Female Labor	0.07870*	0.05880
	(0.04260)	(0.03884)
Capital	-0.01523	-0.01761
	(0.01579)	(0.01802)
Surface Water	0.00699	0.00987
	(0.01291)	(0.04076)

	Kharif	**Rabi**
Hired Labor	0.28784***	0.00045***
	(0.00993)	(0.00003)
Fertilizer	0.10662***	0.10905***
	(0.00997)	(0.01020)
Groundwater	0.00994***	0.24049***
	(0.00150)	(0.01511)
Own Male Labor	-0.01505	-0.01596
	(0.01270)	(0.01165)
Own Female Labor	0.07661*	0.07173*
	(0.04116)	(0.04266)

Capital	-0.01477	-0.01805
	(0.01542)	(0.01611)
Surface Water	0.00736	0.00708
	(0.01135)	(0.01309)

Note: Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

1.6.2 Technical Efficiency

The technical efficiency estimates are producer specific. Table 1.13 reports descriptive statistics on technical efficiency decomposed across different groups of households.

Table 1.13: Estimates of Technical Efficiency (standard errors of the means in parentheses)

	Mean	Median	Min	Max
Overall	0.25	0.20	0.01	1.00
	(0.00)			
Owner-Cultivated	0.22	0.17	0.01	0.99
	(0.01)			
Sharecropped	0.30	0.25	0.02	1.00
	(0.01)			
Fixed-Rent	0.23	0.18	0.01	0.80
	(0.02)			
Small Farm (<4 ha)	0.24	0.19	0.01	1.00
	(0.00)			
Medium Farm (4 to 10 ha)	0.27	0.22	0.01	0.98
	(0.01)			
Large Farm (>10 ha)	0.27	0.22	0.02	0.99
	(0.02)			
With Surface Water	0.28	0.22	0.01	1.00
	(0.01)			
Without Surface Water	0.19	0.17	0.01	0.90
	(0.00)			
Head of Watercourse	0.28	0.24	0.01	1.00
	(0.01)			
Middle of Watercourse	0.27	0.21	0.01	0.99
	(0.01)			
Tail of Watercourse	0.25	0.19	0.02	1.00
	(0.01)			
Rabi	0.24	0.19	0.02	0.99
	(0.01)			
Kharif	0.26	0.21	0.01	1.00
	(0.01)			

The overall mean technical efficiency of the households in the sample is 25 percent. There is significant variation in the mean and median technical efficiency across certain groups of households. The mean and median technical efficiency of sharecroppers is higher than the mean and median technical efficiencies of owner-cultivators and fixed-rent tenants. The median technical efficiency of sharecroppers is 8 percentage points higher than the median technically efficiency of owner-cultivators. I plot the cumulative distribution functions of technical efficiency across tenure type in Figure 1.1 in order to determine whether the technical efficiency of sharecroppers dominates the technical efficiency of owner-cultivators and fixed-rent tenants at all levels of technical efficiency.

Figure 1.1: Cumulative Distribution Functions of Technical Efficiency by Tenancy Type

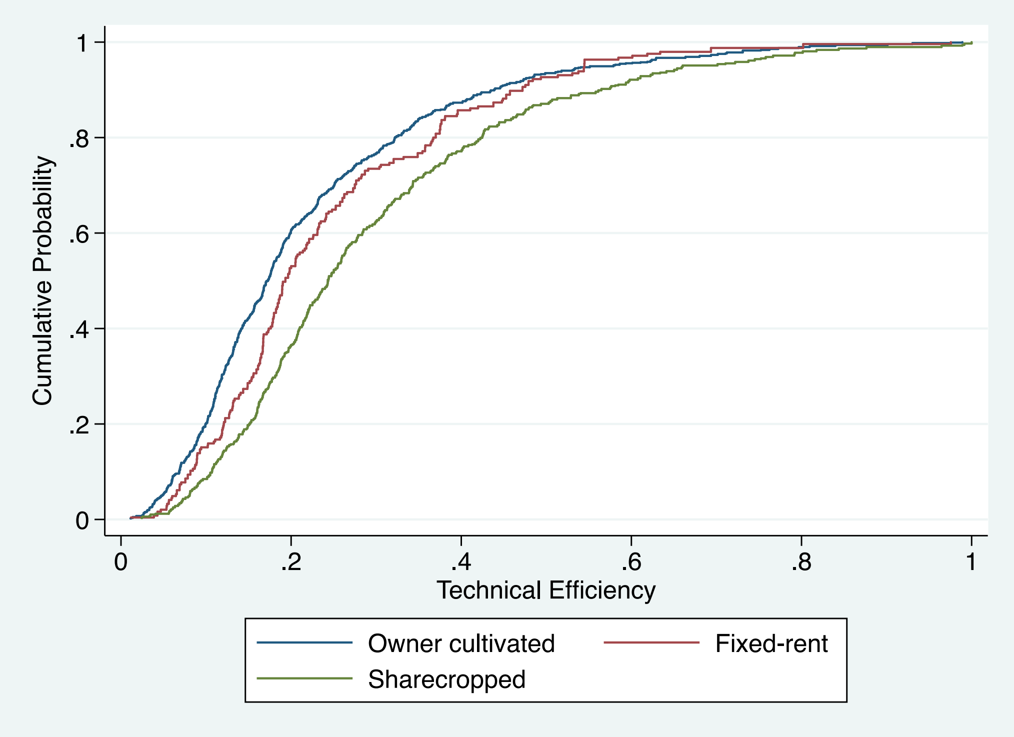
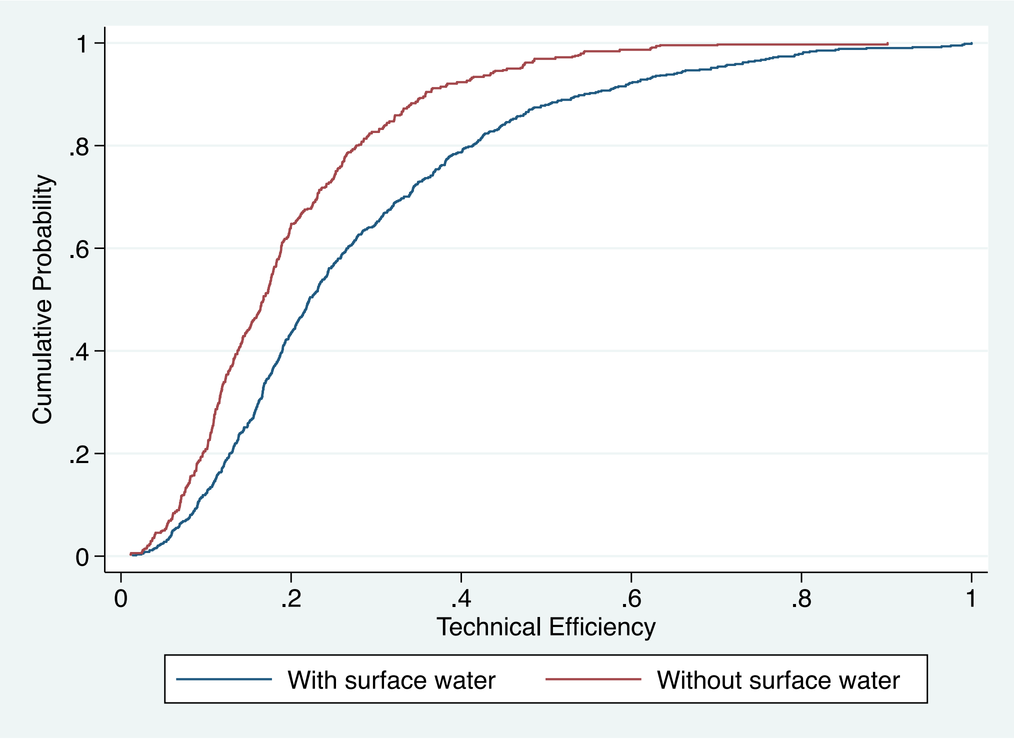


Figure 1.1 shows that the cumulative distribution function of technical efficiency for sharecroppers lies everywhere to the right of the cumulative distributions of owner-cultivators and fixed-rent tenants. The distributions for owner-cultivators and fixed-rent tenants are similar at all levels of technical efficiency. The figure shows that in comparison to the 48 percent of sharecroppers that operate at a technical efficiency level of 25 percent or higher, only 30 percent and 35 percent of owner-cultivators and fixed-rent tenants operate above that level. This is an important finding that is consistent with Jacoby and Mansuri (2009), who do not find evidence of significant differences in the productivity of sharecroppers and owner-cultivators in Pakistan. These finding should be explored further in future research.

There is also a noticeable difference in the mean and median technical efficiency of households with access to surface water and households without surface water. The mean and the median values differ by 9 and 5 percentage points, respectively, across the two groups. These differences are explored further in Figure 1.2, which shows the cumulative distribution functions of technical efficiency for households with and without surface water.

Figure 1.2: Cumulative Distribution Functions of Technical Efficiency for Households with and without Surface Water



The distribution of technical efficiency for households with surface water dominates the distribution for households without surface water at all levels of technical efficiency. The figure shows that about 40 percent of households with surface water operate at a technical efficiency level of 0.25 or more, while only around 20 percent of households without surface water operate at a similar level.

Table 1.13 also shows that technical efficiency of farms differs by the location of the farms on a watercourse. Farms located at the head of the watercourse and at the middle of the course have higher mean and median technical efficiency than farms located at the tail of a watercourse. The median technical efficiency of farms located at the head of the watercourse is 6 percentage points higher than the technical efficiency of farms located at the tail of the watercourse.

My estimates of technical efficiency are lower than estimates in a number of other studies on technical efficiency of farmers in Pakistan. Battese and Sohail (1996) estimated technical efficiency of a sample of wheat farmers across the four provinces of Pakistan under different specifications. Their estimates of mean technical efficiency ranged between 57 percent and 79 percent. Burki and Shah (1998) estimated a mean technical efficiency of 76 percent for farmers in five districts of Punjab. However, Ali et al. (1994) estimated a mean technical efficiency of 24 percent for a sample of farmers in Khyber Pakhtunkhwa (KP) province, known as the North West Frontier Province (NWFP) when that study was conducted. One possible explanation for such differences is that the previous studies focused on more homogenous groups of farmers that either specialized in single crops or belonged to districts in regions with homogeneous conditions. These studies also assumed that the technical efficiency term in the model followed a particular distribution. In my study, I have a more heterogeneous sample of farmers across diverse locations, and I treat technical efficiency as a fixed-effect without assuming it follows a specific distribution. Moreover, Thiam et al. (2001) conducted a meta-analysis of empirical estimates of technical efficiency in agricultural in the stochastic frontier literature. Their results show that the system of equations approach, which is my approach, tends to produce lower estimates of technical efficiency compared with the single equation approach. The system of equation estimates they cite range from 17 percent to 73 percent.

To verify my results, I estimated several single-equation models using the stochastic frontier program in STATA. These included two fixed-effects models and four random-effects models. The random-effects models assumed that technical efficiency followed a particular distribution. The estimate of mean technical efficiency based on both fixed-effects models was 21 percent. In the random-effects models, the estimates of mean technical efficiency ranged between 37 percent and 74 percent. The estimate of mean technical efficiency in my fixed-effects system of equations model falls within the range of the mean technical efficiency estimates of the single-equation models. Furthermore, the correlation between the estimates of technical efficiency in my model and the other six models that were estimated ranges between 0.55 and 0.64, suggesting that even though the means can be quite different, the estimates still contain much of the same information. This exercise suggests that the low estimated values of technical efficiency are likely to be a consequence of the considerable heterogeneity in my sample and the less restrictive assumptions about the technical efficiency term.

1.6.3 Allocative Efficiency of Groundwater

Table 1.14 presents descriptive statistics of the estimates of the producer-specific allocative efficiency of groundwater for farmers who apply groundwater. A positive value of allocative efficiency signifies over-utilization of groundwater and a negative value signifies under-utilization of groundwater. Allocative efficiency increases as its value approaches zero.

Table 1.14: Estimates of Allocative Efficiency of Groundwater (standard errors of the means in parentheses)

	Mean	Median	Min	Max
Overall	0.20 (0.02)	0.22	-2.17	3.99
Owner-Cultivated	0.31 (0.03)	0.32	-2.05	3.99
Sharecropped	-0.09 (0.08)	-0.15	-2.17	1.84
Fixed-Rent	0.04 (0.09)	0.06	-1.78	3.17
Small Farm (<4 ha)	0.28 (0.03)	0.27	-2.17	3.99
Medium Farm (4 to 10 ha)	-0.06 (0.07)	-0.05	-2.04	3.99
Large Farm (>10 ha)	-0.13 (0.10)	-0.13	-2.05	1.35
With Surface Water	0.07 (0.04)	0.06	-2.17	2.55
Without Surface Water	0.32 (0.03)	0.30	-1.57	3.99
Head of Watercourse	0.10 (0.08)	0.12	-2.05	2.06
Middle of Watercourse	0.07 (0.05)	0.08	-2.04	2.34
Tail of Watercourse	0.25 (0.04)	0.28	-2.17	2.55
Rabi	0.06 (0.03)	0.13	-2.05	2.10
Kharif	0.39 (0.05)	0.36	-2.17	3.99

Table 1.14 shows that the mean and median allocative efficiency are greater than zero: 0.20 and 0.22, respectively. Thus, households that use groundwater tend to over-utilize it. The decomposition of allocative efficiency across groups shows considerable variation and provides valuable insights. On average, owner-cultivators and fixed-rent tenants over-utilize groundwater while sharecroppers underutilize it. At the mean and median values of allocative efficiency, fixed-rent tenants are more efficient than owner-

cultivators and sharecroppers. I once again examine the cumulative distribution functions in order to explore these differences in more detail.

Figure 1.3 presents the cumulative distribution functions of allocative efficiency of groundwater across tenure. The distribution for sharecroppers lies to the left of the distribution for owner-cultivators. The distribution for fixed-rent tenants lies uniformly between the other two distributions. Figure 1.3 suggests that 54 percent of sharecroppers underutilize groundwater, compared to around 29 percent of owner-cultivators. This is likely a reflection of the high share of sharecroppers in the sample having access to surface water—as explained later in the section, farms with access to surface water reduce their utilization of groundwater since they rely mainly on surface water to meet their irrigation requirements.

Table 1.15 below shows the descriptive statistics of the share of total farm area with access to surface water across tenure and provinces in the estimation sample. Owner cultivators and sharecroppers in Punjab, on average, have a lower share of total farm area with access to surface water compared to owner cultivators and sharecroppers in Sindh. However, Punjab has a much higher share of owner cultivators (83 percent) than sharecroppers (7 percent), while in Sindh the share of sharecroppers (68 percent) is more than twice the share of owner cultivators (31 percent).

Sharecroppers on average have a higher share of total farm area with access to surface water compared to owner cultivators in the estimation sample. The majority of the total farm area cultivated by fixed-rent tenants in both Punjab and Sindh has access to surface water (62 percent in Punjab and 86 percent in Sindh). Therefore, sharecroppers and fixed rent tenants might use surface water for their primary irrigation needs and underutilize groundwater compared to owner cultivators.

Figure 1.3: Cumulative Distribution Functions of Allocative Efficiency of Groundwater Across Tenure Systems.

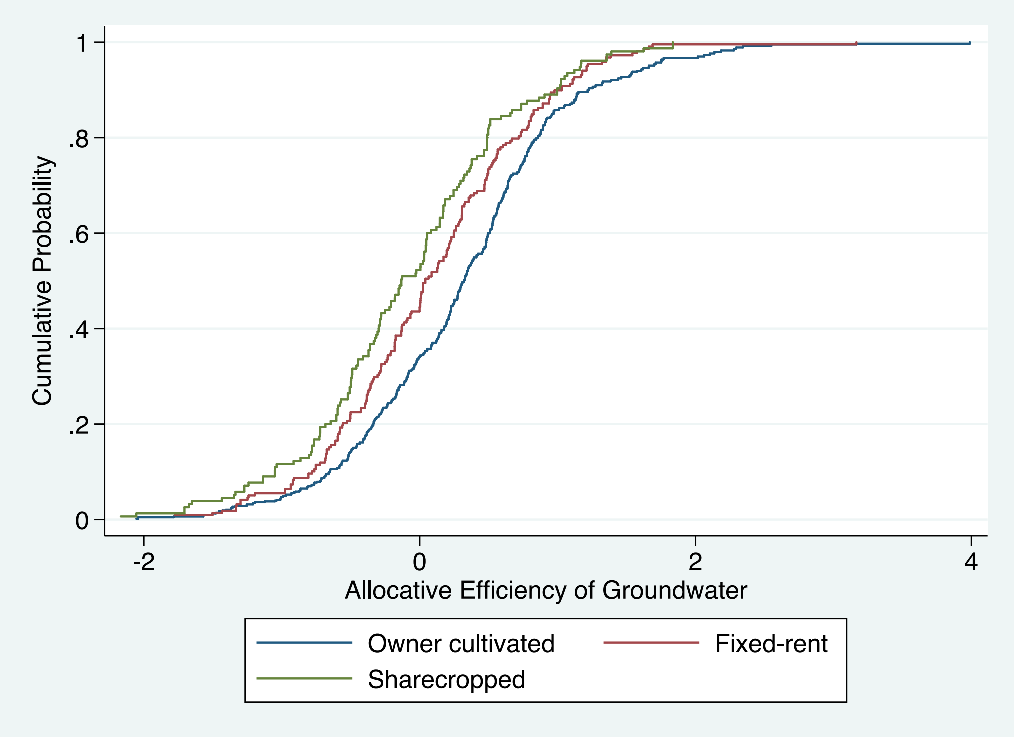


Table 1.15: Share of Total Farm Area with Access to Surface Water Across Tenure and Provinces (percent)

Punjab (58 percent of total farms in the sample)

	Mean	Median	Standard Deviation	Share in Province
Owner Cultivators	39.17	0.00	48.56	83.00
Fixed-Rent Tenants	62.01	100.00	48.80	10.00
Sharecroppers	45.76	0.00	50.25	7.00

Sindh (42 percent of total farms in the sample)

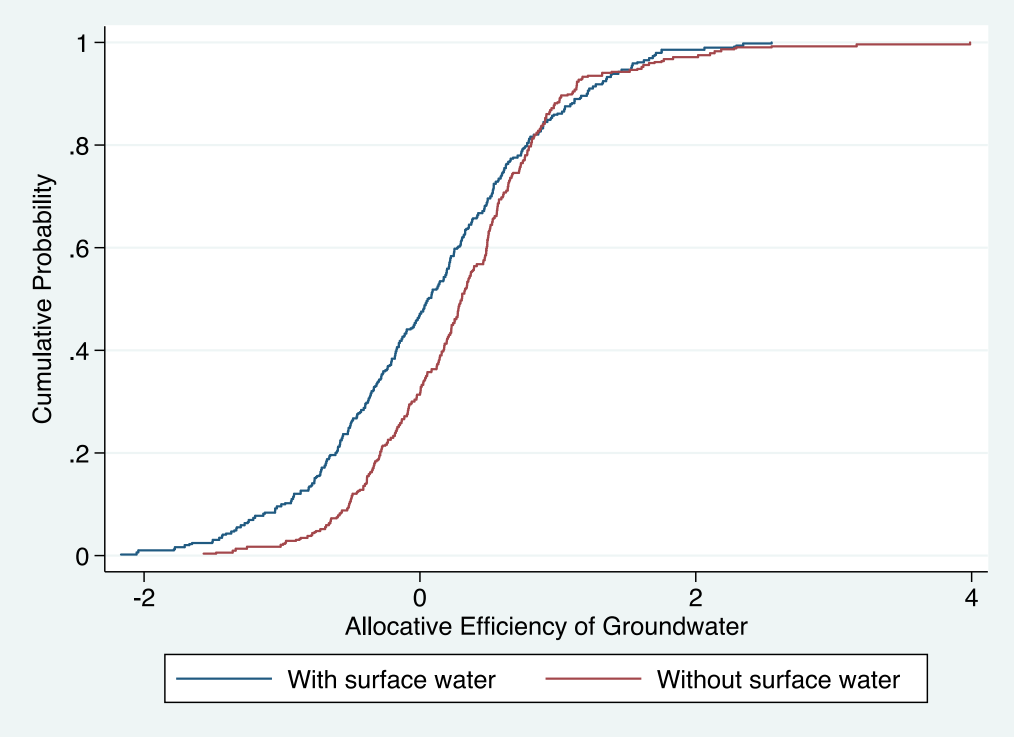
	Mean	Median	Standard Deviation	Share in Province
Owner Cultivators	92.34	100.00	26.65	31.00
Fixed-Rent Tenants	85.71	100.00	37.80	1.00
Sharecroppers	90.95	100.00	28.72	68.00

Note: The statistics are calculated using the 1870 observations in the estimation sample.

Table 1.14 also shows that, on average, farmers with medium-sized farms allocate groundwater efficiently. The mean and median allocative efficiencies are quite close to zero. Small and large farmers, in contrast, are allocatively inefficient. The former over-utilize groundwater while the latter underutilize groundwater on average.

Farms with access to surface water are, on average, more allocatively efficient than farms without surface water, although both tend to over-utilize groundwater. The cumulative distribution functions of allocative efficiency of groundwater across these groups (Figure 1.4) shows that a large portion of the distribution for farms with surface water is strictly to the left of the distribution for farms without surface water. Nearly 75 percent of farms without surface water over-utilize groundwater. Farms with surface water are much more evenly balanced between over- and underutilization, with 56 percent of them over-utilizing it. Most farmers in Pakistan use groundwater together with surface water. Therefore, farmers use less groundwater if their plot also receives surface water, which is cheaper, but less reliable, leading to additional policy related concerns.

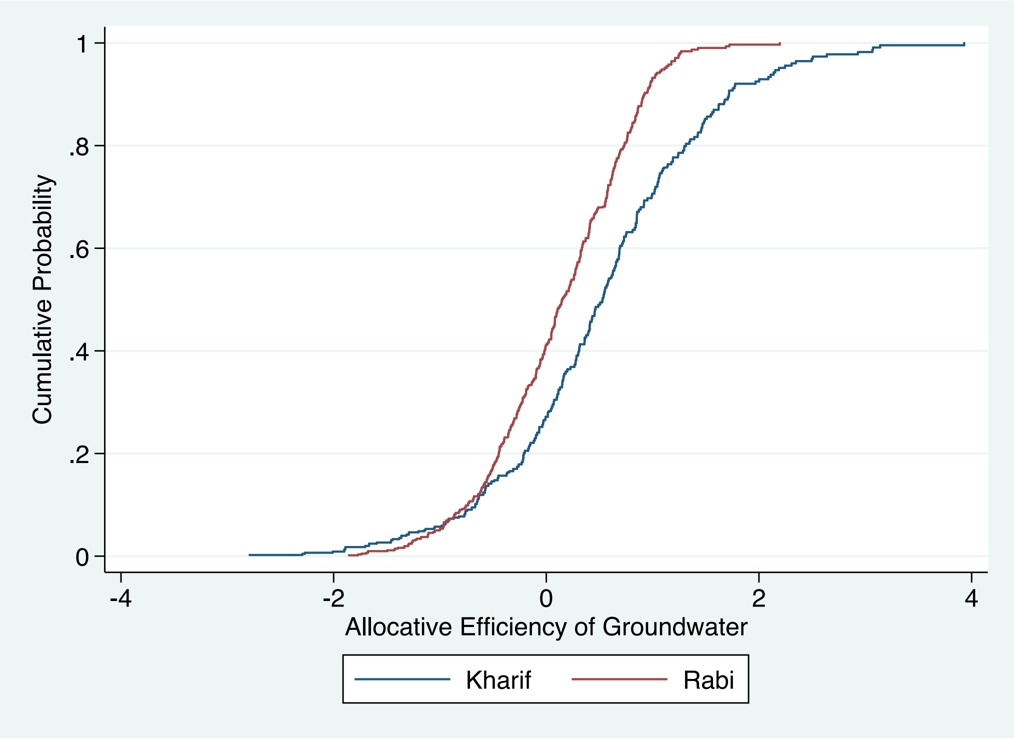
Figure 1.4: Cumulative Distribution Functions of Allocative Efficiency of Groundwater Across Farms With and Without Access to Surface Water.



The allocative efficiency of groundwater varies by the location of the farms on a watercourse. Farms at all three locations of a watercourse (head, middle and tail) tend to over-utilize groundwater. At the mean and median values of allocative efficiency, farms located at the middle of a watercourse are more efficient than farms located at the head and the tail of a watercourse. Farms at the tail of a watercourse are, on average, the most allocatively inefficient. Farms at the tail of a watercourse have a less reliable supply of surface water compared to farms located further up the watercourse and might compensate for the unreliable surface water supply by applying more groundwater.

In terms of seasons, farmers in rabi tend to be more allocatively efficient than farmers in kharif, but both types of farmers overutilize groundwater on average. The cumulative distributions of allocative efficiency for the two seasons are presented in Figure 1.5. It shows that 73 percent of farmers in kharif overutilize groundwater versus 59 percent of farmers in rabi. In my sample farmers produce rice and sugarcane (high water intense crops) in kharif, and wheat (low water intense crop) in rabi. The choice of crop produced could explain the differences in groundwater utilization across seasons, both in terms of crop water needs and in terms of crop profitability. One would wonder what would have happened if farmers had additional options for cropping patterns across the two seasons, which is an important policy question.

Figure 1.5: Cumulative Distribution Functions of Allocative Efficiency for Farmers in the Kharif and Rabi Seasons



The allocative and technical efficiency estimates seem to follow a similar pattern. Sharecroppers on average tend to be more technically and allocatively efficient than owner-cultivators. Similarly, farms with access to surface water are more allocatively and technically efficient than farms without surface water, mainly because they have more flexibility in their allocation process. In order to explore in more depth the relationship between technical efficiency and allocative efficiency, Figure 1.6 graphs allocative efficiency against technical efficiency.

Figure 1.6: Allocative Efficiency versus Technical Efficiency for all Households

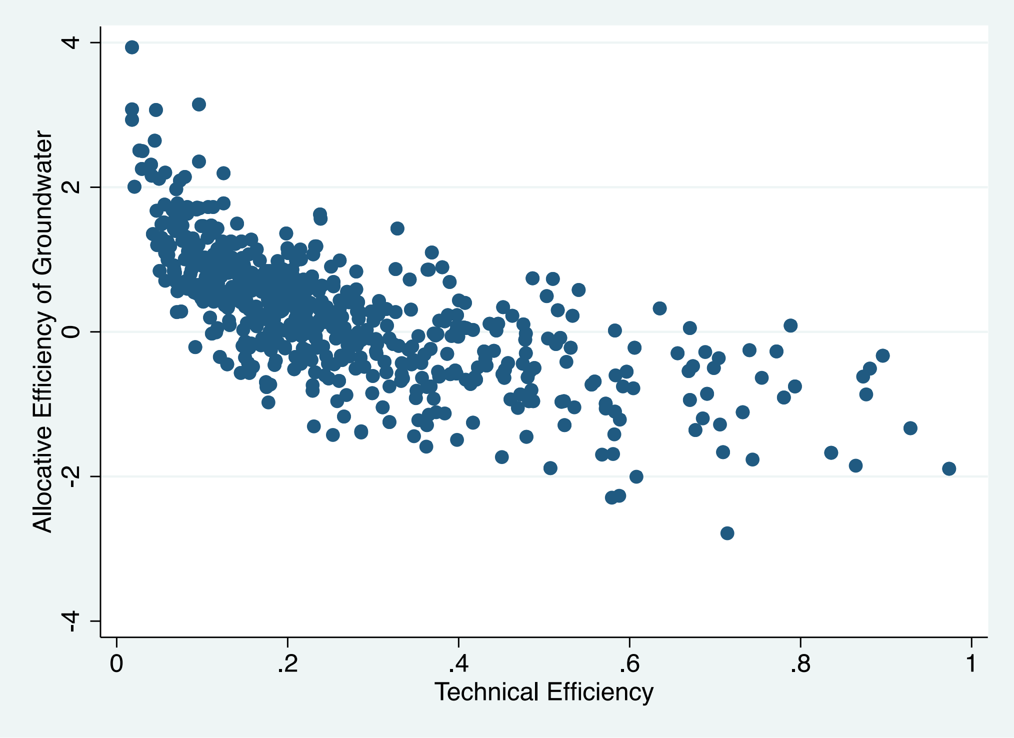


Figure 1.6 indicates a non-linear relationship between technical efficiency and allocative efficiency of groundwater. Farms with values close to the overall mean value of technical efficiency (0.25) are concentrated around the allocatively efficient level of groundwater. Farms with lower values of technical efficiency tend to have higher values of allocative inefficiency, suggesting over-utilization of groundwater. As technical efficiency increases, allocative efficiency falls, at first rapidly, and then more gradually. More technically efficient farms tend to underutilize groundwater. These findings suggest that policies designed to increase technical efficiency need to take into account the resulting effect on allocative efficiency, and vice-versa. The trade-off is quite strong at

low levels of technical efficiency, and becomes much weaker as technical efficiency levels rise.

1.6.4 Results from the Kharif and Rabi Samples

Tables B.1 (Appendix B) and C.1 (Appendix C) show the elasticities of the variable inputs and quasi-fixed inputs in the kharif and rabi samples. The elasticities are calculated at the median values of the inputs and are reported across the overall samples and several household characteristics. In the overall samples fertilizer has the largest impact (0.78) in kharif while groundwater has the largest impact (0.30) in rabi. Groundwater does not have a statistically significant impact on output per hectare in kharif. The elasticity of own male labor is statistically significant and positive in rabi suggesting that own male labor is constrained on farms in the rabi. Moreover, the overall samples show that surface water has a positive and significant impact (0.04) on output per hectare in rabi. This implies that surface water is constrained on farms in rabi. These results show that a marginal increase in the use of both groundwater and surface water would have a significant impact on land productivity in rabi only.

Across tenure, groundwater has the largest impact on output per hectare on owner-cultivated and fixed-rent farms when rabi farmers are considered. The elasticity of groundwater is zero across all types of tenure in kharif. Surface water has a significant impact on output per hectare on owner-cultivated and sharecropped farms in rabi. Moreover, the elasticity of capital is positive and significant for sharecropped farms in rabi.

When elasticities are compared across farm size, the impact of hired labor is larger on medium and large farms. This impact is significantly more pronounced in rabi. The impact of groundwater on output per hectare is similar across small, medium and large farms in rabi and is zero across the three farm sizes in kharif. The elasticity of surface water is also significant and similar in rabi and equal to zero in kharif across small, medium and large farms.

Groundwater per hectare has the largest impact on land productivity on rabi farms with surface water. The impact of groundwater on output per hectare in kharif is zero on farms with and without surface water. Table C.1 also shows that surface water has a significant impact on output per hectare on farms without surface water. These are farms that are not located on the watercourse and are most likely irrigated with surface water purchased from neighboring farms.

The results from the separate season show that a marginal increase in the use of both groundwater and surface water would have a significant impact on land productivity in rabi only. These inputs are not constrained in kharif and a marginal increase in these inputs in kharif will not have a positive impact on output per hectare. Fertilizer, on the other hand, has a significantly larger impact on land productivity in kharif than in rabi. Output per hectare in kharif would benefit from a marginal increase in the use of fertilizer.

1.6.5 Technical Efficiency (Season Samples)

Tables B.2 and C.2 present the producer-specific technical efficiency estimates from the kharif and rabi samples across different household characteristics. In kharif the overall mean technical efficiency of households is 18 percent while in rabi the overall mean technical efficiency of households is 26 percent. The mean and median technical efficiency of sharecroppers is higher than the mean and median technical efficiency of owner-cultivators and fixed-rent tenants in kharif. In rabi the mean technical efficiency of fixed-rent tenants is higher than the mean technical efficiency of sharecroppers and owner-cultivators. However, at the median values of technical efficient sharecroppers are more technically efficient than owner-cultivators and fixed-rent tenants.

In Figures B.1 and C.1 I plot the cumulative distribution functions of technical efficiency in kharif and rabi across tenure type. The distribution of technical efficiency for sharecroppers lies to the right of the distribution of technical efficiency for owner-cultivators in both seasons. In kharif, 40 percent of sharecroppers and 20 percent of owner-cultivators operate at a technical efficiency level of 20 percent or higher. In rabi, on the other hand, 70 percent of sharecroppers and 50 percent of owner-cultivators operate at a technical efficiency level of 20 percent or higher.

Tables B.2 and C.2 also show that the differences in the mean and median technical efficiencies across farm size and access to surface water are more pronounced in rabi than in kharif. Households with large farms in rabi are 9 percent (at the mean) and 12 percent (at the median) more technically efficient than households with small farms in rabi. In kharif the mean technical efficiency of households with medium farms is a percentage point greater than the mean technical efficiency of households with large farms. At the median, the technical efficiency of households with medium farms is a percentage point lower than the technical efficiency of households with large farms. Households with small farms in both seasons have the lowest mean and median values of technical efficiency.

The mean technical efficiency of households in rabi with access to surface water is 11 percent higher than the mean technical efficiency of households in rabi without access to surface water. This difference falls to 9 percent when the median values of technical efficiency are considered. In kharif the differences in the mean and median technical efficiency of households with surface water and households without surface water are 3 percent and 2 percent respectively. Figures B.2 and C.2 show the plots of the cumulative distribution functions of technical efficiency in kharif and rabi across access to surface water. The gap in the distributions is more pronounced in rabi compared to kharif. In rabi, 75 percent of households with access to surface water and 45 percent of households without access to surface water operate at a technical efficiency level of 0.2 percent or higher. However, in kharif this difference is only 15 percent at the same level of technical efficiency.

When the location of the farms on a watercourse is considered, households with farms located at the head of the watercourse in kharif are 3 percent (at the mean) and 4 percent (at the median) more technically efficient than households with farms located at the tail of the watercourse. In rabi the mean technical efficiency of households with farms located at the middle of the watercourse is 2 percent higher than the mean technical efficiency of households with farms located at the head of the watercourse. However, at the median value the technical efficiency of households with farms located at the head of the watercourse is a percentage point greater than the technical efficiency of households with farms located at the middle of the watercourse. In both seasons, households with farms located at the tail of the watercourse have the lowest mean and median technical efficiency. The mean technical efficiency of households located at the tail of the watercourse in rabi is 7 percent higher than the mean technical efficiency of households located at the head of the watercourse in kharif. This demonstrates the superior technical efficiency of households in rabi compared to households in kharif.

6.6 Allocative Efficiency (Season Samples)

Tables B.3 and C.3 show the estimates of the allocative efficiency of groundwater from the kharif and rabi samples across several household characteristics. On average, households in kharif overutilize groundwater while households in rabi underutilize groundwater. The median value of efficiency suggests that households are allocatively efficient in rabi.

The estimates across tenure show that owner-cultivators, sharecroppers and fixed-rent tenants overutilize groundwater in kharif although sharecroppers tend to be more allocatively efficient than owner-cultivators and fixed-rent tenants. In rabi owner-cultivators overutilize groundwater while sharecroppers and fixed-rent tenants underutilize groundwater. Owner-cultivators are more efficient than sharecroppers and fixed-rent tenants at both the mean and median values of allocative efficiency. The differences in allocative efficiency across tenure in kharif and rabi are explored further through the cumulative distributions given in figures B.3 and C.3. Figure B.3 shows that all households under each type of tenure overutilize groundwater in kharif. Figure C.3 on the other hand shows that in rabi 60 percent of owner-cultivators overutilize groundwater compared to sharecroppers.

Results across farm size show that in kharif large farms are more allocatively efficient than small and medium farms. In rabi, however, small farms are more allocatively efficient, compared to medium and large farms. Groundwater is overutilized in kharif across all farm sizes. In rabi, groundwater is on average underutilized across all farm sizes. However, at the median value of efficiency small farms in rabi tend to overutilize groundwater.

The results of allocative efficiency across access to surface water differ across seasons, as well. In kharif, households with access to surface water and households without access to surface water overutilize groundwater, although the former group tends to be more allocatively efficient. In rabi, households with surface water tend to underutilize groundwater, while households without surface water tend to overutilize ground water. Figure B.4 presents the cumulative distribution of allocative efficiency across access to surface water in rabi. The figure shows that 60 percent of households in rabi without access to surface water overutilize groundwater, compared to 30 percent of households in rabi with access to surface water.

The estimates across location on a watercourse show that households with farms located at the head, middle and tail of the watercourse over-utilize groundwater in kharif.

The mean allocative efficiency of groundwater is similar for households with farms at the head and the middle of the watercourse. Households with farms at the tail of the watercourse are more allocatively inefficient compared to households with farms located at the head and the middle of the watercourse. In rabi, households, on average, underutilize groundwater across all three locations on a watercourse (head, middle and tail). At the median value of allocative efficiency households with farms located at the tail of the watercourse tend to overutilize groundwater. Households with farms located at the head of the watercourse are on average more allocatively efficient than households with farms located at the tail of the watercourse. However, when the median value of allocative efficiency is considered, households located at the tail of the watercourse are more allocatively efficient than households with farms located at the head of the watercourse.

The results of the allocative efficiency of groundwater by season and across different household characteristics show that all farmers in kharif overutilize groundwater. In rabi, a part of the distribution of allocative efficiency lies to the right of zero, which shows that some farmers underutilize groundwater in rabi. Policies designed to improve the allocative efficiency of groundwater need to take into account the differences in groundwater use across seasons.

1.7 Summary and Conclusions

This chapter provided an empirical analysis of groundwater use in Pakistan's agricultural sector. Using a rural household panel dataset from Pakistan, which spans over the period 2000-01 to 2003-04, I examined the utilization and allocative efficiency of groundwater, and compared it across a number of important farm characteristics. I found evidence that the efficiency of groundwater use varies considerably across these characteristics, including different types of tenure arrangements. The results from the study suggest avenues for policy research on the management of irrigation water across agricultural tenure systems. Simulations of the impact of a set of water policy reforms on the allocative efficiency of irrigation water, and on agricultural incomes and poverty, will shed light on the efficacy of these policy alternatives. The results of these simulations will be reported in a separate chapter.

Pakistan's agrarian structure was examined across two provinces, two seasons, and two periods. Because the PRHS-II dataset included households solely from Punjab and Sindh, the econometric analysis was restricted to these provinces. Similarly, because plots were not identified uniquely across the survey waves, the panel dataset was constructed at the household level. Households were analyzed in both the rabi and kharif seasons.

The discussion on tenancy emphasized the importance and structure of tenure arrangements in Punjab and Sindh. It showed that owner-cultivation was the most common form of tenancy in Punjab and Sindh, accounting for around 59 percent of the cultivated plots and a similar share of area in the first wave of the panel. Sharecropping was also quite important across Punjab and Sindh, accounting for around 34 percent of the plots in PRHS-I. Fixed-rent tenancy, in contrast, comprised only around 10 percent of the plots and area in the first wave of the survey. The share of plots, and the average plot area, under each form of tenancy varied little over time, although a modest decline in the importance of sharecropping was observed. Since incentives under each form of tenure differ, the relative stability of tenancy across seasons and years shows the relatively static nature of the institutional constraints on farmers in this period.

The descriptive analysis of irrigation water availability in Pakistan showed that irrigation is an important input in agricultural production in Punjab and Sindh. In these provinces, around 60 percent of plots had access to groundwater, 70 percent had access to surface water, and 50 percent had access to both. Overall, 85 percent of the agricultural plots in Punjab and Sindh had access to surface water, groundwater or both.

The chapter also presents evidence on the availability of both forms of irrigation water in Punjab and Sindh, according to the position of the farms on the watercourse. All the plots located at the head of the watercourse had access to surface water, groundwater, or both. Similarly, all the plots at the tail of the watercourse in these two provinces also had access to either one or both forms of irrigation. The analysis showed that irrigation availability and location on the watercourse were constraints that might influence the utilization of groundwater and should be included as control variables in the estimation of the allocative efficiency of groundwater.

The estimation of elasticities from the pooled sample showed that groundwater per hectare had the largest marginal effect on output per hectare across most farm groups.

Surface water per hectare, in contrast, did not have a significant effect on land productivity across any of a number of farm groups. When the model was estimated for each season separately, the impact of groundwater on land productivity was not statistically significant. However, groundwater per hectare had the largest marginal impact on land productivity in rabi. The effect of surface water became pronounced in the rabi sample but was zero in the kharif sample. Hussain et al. (2000) reached a similar conclusion. Low surface water charges have been suggested as a cause for over-use of surface water, poor maintenance of irrigation infrastructure (through lack of resource generation), and failure to move scarce water to higher value uses (Shah et al. 2009). It is likely that these factors contribute to the elasticity estimates for surface water. Increasing surface water charges might address these issues and will be explored in the future.

Estimation results show that sharecroppers operate closer to the production frontier than owner-cultivators, although there was a high degree of inefficiency for both groups. This result holds on average, and at every percentile of the technical efficiency distribution. Jacoby and Mansuri (2009) show that the average land productivity of owner-cultivators and supervised sharecroppers – the majority of sharecroppers in Pakistan – is statistically equal. Combining their results and ours suggests that sharecroppers compensate for other deficiencies – such as access to credit, capital, or irrigation – through superior technical efficiency.

The results for the allocative efficiency of groundwater showed significant differences in the utilization of groundwater across tenure, farm size, access to surface water and location on a watercourse. Allocative efficiency measures the extent to which the marginal product of an input differs from the price of the input. The inability of farmers to adjust to changes in relative input prices might be related to the differential constraints that they face across groups. The literature review identified cultivation experience, access to credit, capital intensity, and agricultural extension as some of the additional constraints on farmers. Future policy work will focus on examining the effect of these farm-level differential constraints on groundwater use.

The market structure for groundwater might also explain part of the estimated allocative efficiency. Jacoby et al. (2001) show that tubewell owners in Pakistan have some market power over groundwater and charge a lower price to their share tenants, compared to the price charged to other buyers. This price discrimination leads tubewell owners and their share tenants to use more groundwater per hectare on their land than buyers of groundwater. The allocative efficiency of groundwater across tubewell owners, their tenants, and purchasers of groundwater requires further investigation.

Farms with access to both surface water and groundwater allocate groundwater more efficiently than farms that have access to only groundwater. Given the fixed allocations of surface water, and its unreliability, farms with access to surface water might not meet their irrigation requirements with surface water alone. These farms might use groundwater to meet possible irrigation deficits. However, farms with only groundwater do not have any additional source of irrigation to meet their water requirements. Hence, these farms might overutilize groundwater. Since groundwater use depends on the availability of surface water, in future policy work I will simulate the effect of increasing the access to surface water on the allocative efficiency of groundwater.

Access to surface water explains some of the differences in the allocative efficiency of groundwater observed across tenure. Sharecroppers and fixed-rent tenants have, on average, a higher share of total farm area with access to surface water compared to owner cultivators. Since access to surface water allows farms to meet their irrigation requirements through surface water, sharecroppers and fixed-rent tenants tend to utilize less groundwater compared to owner cultivators.

The allocative efficiency of groundwater is also related to the location of the farms on a watercourse. Farms located at the head of the watercourse tend to be more allocatively efficient than farms located at the tail of the watercourse. Since the allocation of surface water is uniform (fixed per unit of land) across all locations of a watercourse, farmers located at the tail of the watercourse are at a disadvantage given the unreliable supply of surface water. Simulating the impact of a more equitable allocation of surface water across head and tail-end users on farms operations could shed light on the changes in the allocative efficiency of groundwater.

Farms overutilize groundwater across both seasons, but on average are more allocatively efficient in rabi than in kharif. Since rabi is the dry season, the shadow value of water from all sources is higher in rabi. Moreover, wheat – a crop with a relatively low level of water needs – is the only major crop grown in rabi. It needs to be irrigated less frequently than rice and sugarcane – two of the three main kharif crops. The policy simulations proposed above will take into account the seasonal differences in farm operations and farm-level constraints.

The analysis in this chapter showed that improvement in the technical efficiency of farms is likely to have a complicated relationship with the allocative efficiency of groundwater. At low levels of technical efficiency – where many farms operate – there appears to be scope for improving technical and allocative efficiency simultaneously. But at higher levels of technical efficiency there is a trade-off. Thus, the constraints that affect the technical efficiency of farms could also indirectly affect farms' allocative efficiency, but the direction of the impact would depend on the level of technical efficiency. Policy simulations will take these interactions into account.

This study found evidence that suggests drawbacks and limitations of the current institutional environment of irrigation water management in Pakistan. In the third chapter of the dissertation, the analysis of the allocative efficiency of groundwater will address some of the most important water policy reforms that have been proposed. The efficacy of any proposed set of water policy reforms will depend on the prevailing institutional environment of water management. Placing potential reforms in this context should help determine the feasibility of these policies. The combination of empirical and policy results could help fill a knowledge gap about alternatives for the sustainable and productive use of irrigation water in Pakistan.

Chapter 2: Optimal Groundwater Management in Pakistan's Indus Water Basin

2.1 Introduction

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. The core water management issues for irrigation in Pakistan include: low water charges for users, limited water storage capacity, inequitable distribution of water 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.

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. The quality of groundwater has also deteriorated in certain parts of the Basin (Qureshi et al. 2009).

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 in part 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[14] 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.

In this chapter, I examine the management of groundwater in Pakistan's Indus Basin through a model of groundwater extraction with hydrologic, economic and tenure constraints. I 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.

I 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. It is a model that emphasizes long run dynamics and helps me examine the impact of various

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[14] I use the terms optimal management and optimal control interchangeably throughout the chapter.

economic and hydrological parameters on aquifer recharge, groundwater pumping, water table height, groundwater quality and net benefits. These results can be used to understand the variation in the aquifer characteristics observed spatially within the Indus Basin.

In this chapter, I 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. I develop a dynamic optimization problem to illustrate long-run steady states of groundwater pumping under different management, hydrologic, economic and tenure assumptions. This study emphasizes the sustainability of the aquifer in the Indus Water Basin under different groundwater management schemes. I 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 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 2.3 I model groundwater extractions under various hydrological, economic, management and tenure assumptions. I examine the results of the model simulations in Section 2.4. In Section 2.5 I describe various policies that could lead to optimal groundwater extractions and more effective management of groundwater resources. Section 2.6 concludes the chapter.

2.2 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 (Koundouri 2004). 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 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:

$$\pi(t) = V[w(t)] - C[H(t)]w(t) \tag{2.1}$$

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:

$$\dot{H} = \frac{1}{AS}[R + (a-1)w], \quad H(0) = H_0 \tag{2.2}$$

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 (2.2) 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.[15]

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[15] My model relies on most of the assumptions listed here. However, I 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.

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) 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 I 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 aquifer 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. I address this topic in this chapter 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, these authors 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 tenant farmers can significantly increase input intensity and land productivity. Nasim et al. (2014) 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 owning 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. I 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, I exclude fixed-rent tenancy from the analysis. To my knowledge, this is the first groundwater optimal control study on the aquifer in the Indus Basin and to include the effect of tenure on groundwater extraction decisions.

2.3 Methodology

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

2.3.1 Hydrological-Economic Model of Groundwater Extraction

I 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 I develop links hydrological and economic variables of groundwater usage. I calibrate the model using data from Punjab since the majority of groundwater extractions (90 percent) in the Indus Water Basin occur in Punjab.[16] I begin by defining the water demand, marginal cost, and net benefit functions and then connect these with the characteristics of the aquifer. I acknowledge that changes in land use, cropped area and cropping intensity are important in determining net benefits over time but since my focus is solely on groundwater extractions I use simplified yet reasonable assumptions to keep the model tractable.

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

I 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:

$$P(Q_t) = a_0 - a_1 Q_t \tag{2.3}$$

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:

$$R(Q_t) = \int_0^{(1-\beta_{SW})Q_{SW_t}+Q_{GW_t}} P(Q_t) \, . \, dQ_t \tag{2.4}$$

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

$$MEC\left(Q_{GW_t}\right) = \gamma(H_L - H_t) \tag{2.5}$$

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:

$$C\left(Q_{GW_t}\right) = \int_0^{Q_{GW_t}} MEC(Q_{GW_t}) \, . \, dQ_{GW_t} \qquad (2.6)$$

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).

I 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:

$$c_{gw_t} = \frac{K_t}{AS_y H_t} \tag{2.7}$$

I 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:

$$\pi_t = \left(\int_0^{(1-\beta_{SW})Q_{SW_t}+Q_{GW_t}} P(Q_t)\cdot dQ_t - \int_0^{Q_{GW_t}} MEC\left(Q_{GW_t}\right)\cdot dQ_{GW_t}\right)\ \left(1-\delta c_{gw_t}\right) \tag{2.8}$$

$$\pi_t = \left(\int_0^{(1-\beta_{SW})Q_{SW_t}+Q_{GW_t}} (a_0 - a_1 Q_t)\cdot dQ_t - \int_0^{Q_{GW_t}} \gamma(H_L - H_t)\cdot dQ_{GW_t}\right)\ \left(1-\delta\left(\frac{K_t}{AS_y H_t}\right)\right) \tag{2.9}$$

$$\pi_t = \left(a_0\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right) - \frac{a_1}{2}\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right)^2 - \gamma(H_L - H_t)Q_{GW_t}\right)\left(1 - \delta\left(\frac{K_t}{AS_y H_t}\right)\right) \tag{2.10}$$

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. I 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:

$$H_{t+1} = H_t + \frac{\beta_{SW} Q_{SW_t} + \beta_{DP}\left((1-\beta_{SW})Q_{SW_t} + Q_{GW_t}\right) + \omega - Q_{GW_t}}{AS_y} \tag{2.11}$$

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:

$$H_{t+1} - H_t = \frac{\beta_{SW} Q_{SW_t} + \beta_{DP}\big((1-\beta_{SW})Q_{SW_t} + Q_{GW}^{SS}\big) + \omega - Q_{GW}^{SS}}{AS_y} = 0 \qquad (2.12)$$

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) I use the following equation of motion of groundwater quality:

$$K_{t+1} = K_t + c_{sw} Q_{SW_t} + c_\omega \omega \qquad (2.13)$$

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. I convert the total salt mass into a concentration using equation (2.7) and report the dynamics of this concentration in the results section below.

2.3.2 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:

$$Q_{GW_t} \geq 0$$

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

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

$$0 \leq H_t \leq 375$$

$$H_0 = 370$$

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

$$c_{gw_0} = 2.0$$

The boundary constraint $0 \leq H_t \leq 375$ states that the water table height has to be positive and cannot exceed 375 m. Since the surface elevation is 380 m I 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 $0 \leq c_{gw} < 4.0$ 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:

$$V(H_0, K_0) = Max_{Q_{GW_t}} \sum_{t=0}^{\infty} \alpha^t \Bigg[\Big(a_0 \big((1-\beta_{SW}) Q_{SW_t} + Q_{GW_t} \big) -$$

$$\frac{a_1}{2} \big((1-\beta_{SW}) Q_{SW_t} + Q_{GW_t} \big)^2 - \gamma (H_L - H_t) Q_{GW_t} \Big) \left(1 - \delta \left(\frac{K_t}{AS_y H_t} \right) \right) \Bigg]$$

Subject to the constraints:

$$Q_{GW_t} \geq 0$$

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

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

$$0 \leq H_t \leq 375$$

$$H_0 = 370$$

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

$$c_{gw_0} = 2.0$$

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:

$$V(H, K) = Max_{Q_{GW}}\left[\pi(H, K, Q_{GW}) + \alpha V[g(H, K, Q_{GW})]\right] \tag{2.14}$$

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 (2.12) and the groundwater salt mass (2.13).

The dynamic programming problem consists of solving the Bellman equation (2.14) for the unknown value function V and optimal extractions as functions of the state variables. I 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.

2.3.3 Data Sources

Table 2.1 below shows the values of the parameters used to simulate the baseline model. I 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 2.1: Model Parameters

Parameter	Description	Value
a_0	Intercept of the water demand function	18.91 Rs/Bm^3
a_1	Slope of the water demand function	0.19 $Rs/Bm^3 \cdot Bm^3$
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

I 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). I 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.[17] 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). I 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. I used data for the period 2004-2013 from the *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.

2.3.4 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

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

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 (2.10)—the expression for the annual net benefit from irrigated agriculture in Punjab—I get:

$$\left(a_0(99.52) - \frac{a_1}{2}(99.52)^2 - 22.28\right)(0.75) = 704 \tag{2.15}$$

The first order condition for profit maximization implies:

$$P(Q_t) = MEC\left(Q_{GW_t}\right) \tag{2.16}$$

$$a_0 - a_1\left((1 - \beta_{SW})Q_{SW_t} + Q_{GW_t}\right) = \gamma(H_L - H_t) \tag{2.17}$$

Using the values above for Q_{SW_0}, Q_{GW_0}, β_{SW}, γ, H_L and H_0 and substituting these into equation (2.17) I get:

$$a_0 - a_1(99.52) = 0.4 \tag{2.18}$$

After solving equation (2.15) and equation (2.18) I get:

$$a_0 = 18.91\ Rs/Bm^3$$

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

I use the calibrated water demand function along with the cost and hydrological parameters described earlier to conduct my 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.

2.3.5 Inclusion of Tenure

I 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. I 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. I 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 (Braverman and Stiglitz 1986).

From equation (2.3) I know that the water demand function can be written as:

$$Q(P_t) = \frac{a_0}{a_1} - \frac{P_t}{a_1} \tag{2.19}$$

Using the superscripts OC and SC to denote owner cultivators and sharecroppers respectively, I disaggregate the water demand function given by equation (2.19) into separate water demand functions for owner cultivators and sharecroppers:

$$Q^{OC}(P_t) = \delta^{OC}\left(\frac{a_0}{a_1} - \frac{P_t}{a_1}\right) \tag{2.20}$$

$$Q^{SC}(P_t) = \delta^{SC}\left(\frac{a_0}{a_1} - \frac{P_t}{a_1}\right) \tag{2.21}$$

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

From equations (2.20) and (2.21) the inverse water demand functions for owner cultivators and sharecroppers are given by:

$$P^{OC}(Q_t) = a_0 - \frac{a_1}{\delta^{OC}}\, Q_t \tag{2.22}$$

$$P^{SC}(Q_t) = a_0 - \frac{a_1}{\delta^{SC}}\, Q_t \tag{2.23}$$

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:

$$Q_{SW_t}^{OC} = \delta^{OC}\bar{Q}_{SW_t} \tag{2.24}$$

$$Q_{SW_t}^{SC} = \delta^{SC}\bar{Q}_{SW_t} \tag{2.25}$$

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

$$\pi_t^{OC} = \left(\int_0^{(1-\beta_{SW})Q_{SW_t}^{OC}+Q_{GW_t}^{OC}} P^{OC}(Q_t).\,dQ_t - \int_0^{Q_{GW_t}^{OC}} MEC\big(Q_{GW_t}\big)\,.\,dQ_{GW_t} + (f)\int_0^{(1-\beta_{SW})Q_{SW_t}^{SC}+Q_{GW_t}^{SC}} P^{SC}(Q_t).\,dQ_t - (v)\int_0^{Q_{GW_t}^{SC}} MEC\big(Q_{GW_t}\big)\,.\,dQ_{GW_t}\right)\left(1 - \delta\left(\frac{K_t}{AS_yH_t}\right)\right) \tag{2.26}$$

$$\pi_t^{SC} = \left((1-f)\int_0^{(1-\beta_{SW})Q_{SW_t}^{SC}+Q_{GW_t}^{SC}} P^{SC}(Q_t).\,dQ_t - (1-v)\int_0^{Q_{GW_t}^{SC}} MEC\big(Q_{GW_t}\big)\,.\,dQ_{GW_t}\right)\left(1 - \delta\left(\frac{K_t}{AS_yH_t}\right)\right) \tag{2.27}$$

where f and v are the landlords' share of the output and groundwater cost respectively. Equation (2.26) 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 (2.27) 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:

$$P^{OC}(Q_t) = MEC\big(Q_{GW_t}\big) \tag{2.28}$$

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

$$a_0 - \frac{a_1}{\delta^{OC}}\, Q_t = \gamma(H_L - H_t) \tag{2.29}$$

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

$$Q_{GW_t}^{OC^*} = \frac{\delta^{OC}\big(a_0 - \gamma(H_L - H_t)\big) - a_1(1 - \beta_{SW})Q_{SW_t}^{OC}}{a_1} \tag{2.30}$$

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

$$(1 - f)P^{SC}(Q_t) = (1 - v)MEC\big(Q_{GW_t}\big) \tag{2.31}$$

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

$$Q_{GW_t}^{SC^*} = \frac{\delta^{SC}\big((1 - f)a_0 - (1 - v)\gamma(H_L - H_t)\big) - a_1(1 - f)(1 - \beta_{SW})Q_{SW_t}^{SC}}{a_1(1 - f)} \tag{2.32}$$

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 I assume that monitoring costs are high, sharecroppers lack access to insurance markets and production is risky. I 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 I 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. I have to recalibrate the water demand function to account for difference in the optimization behavior of sharecroppers. I use the base year (2009-2010) values from the pervious calibration to calibrate the tenure model.

Using the optimality conditions given in equations (2.30) and (2.32), the optimal extractions $(Q_{GW_t}^{OC^*} + Q_{GW_t}^{SC^*})$ in the base period are:

$$Q_{GW_0}^{*} = \frac{\delta^{OC}(a_0 - \gamma(H_L - H_0)) - a_1(1-\beta_{SW})Q_{SW_0}^{OC}}{a_1} + \frac{\delta^{SC}((1-f)a_0 - (1-v)\gamma(H_L - H_0)) - a_1(1-f)(1-\beta_{SW})Q_{SW_0}^{SC}}{a_1(1-f)} \tag{2.33}$$

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). I 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:

$$\pi_0 = \left(\int_0^{(1-\beta_{SW})Q_{SW_0}^{OC} + Q_{GW_0}^{OC}} \left(a_0 - \frac{a_1}{\delta_t^{OC}} Q_0\right).dQ_0 - \int_0^{Q_{GW_0}^{OC}} \gamma(H_L - H_0).dQ_{GW_0} + (f)\int_0^{(1-\beta_{SW})Q_{SW_0}^{SC} + Q_{GW_0}^{SC}} \left(a_0 - \frac{a_1}{\delta_t^{SC}} Q_0\right).dQ_0 - (v)\int_0^{Q_{GW_0}^{SC}} \gamma(H_L - H_0).dQ_{GW_0}\right) \left(1 - \delta\left(\frac{K_0}{AS_y H_0}\right)\right) + \left((1-f)\int_0^{(1-\beta_{SW})Q_{SW_0}^{SC} + Q_{GW_0}^{SC}} \left(a_0 - \frac{a_1}{\delta_t^{SC}} Q_0\right).dQ_0 - (1-v)\int_0^{Q_{GW_0}^{SC}} \gamma(H_L - H_0).dQ_{GW_0}\right) \left(1 - \delta\left(\frac{K_0}{AS_y H_0}\right)\right) \tag{2.34}$$

Using values of the various parameters and variables from the previous calibration I solve the system of equations given by equations (2.33) and (2.34) 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:

$$H_{t+1} = H_t + \frac{\beta_{SW}\left(Q_{SW_t}^{OC}+Q_{SW_t}^{SC}\right)+\beta_{DP}\left((1-\beta_{SW})\left(Q_{SW_t}^{OC}+Q_{SW_t}^{SC}\right)+\left(Q_{SW_t}^{OC}+Q_{SW_t}^{SC}\right)\right)+\omega-\left(Q_{SW_t}^{OC}+Q_{SW_t}^{SC}\right)}{AS_y} \quad (2.35)$$

$$K_{t+1} = K_t + c_{sw}\left(Q_{SW_t}^{OC} + Q_{SW_t}^{SC}\right) + c_\omega \omega \quad (2.36)$$

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 I present results for the long run dynamics of the water table height, the groundwater salt concentration, groundwater extractions and the annual net benefits.

2.4 Results

In this section I first present the results of the baseline model. I then describe the various sensitivity analyses that I conducted and present their results. In the final subsection I present the results of the tenure model. Table 2.2 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 the 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 (first 50 years), which might be a more appropriate time horizon for devising policies for groundwater sustainability.

2.4.1 Baseline Results

Figure 2.1 below shows the dynamics of the water table height under the common property regime and under optimal management.[18] 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.

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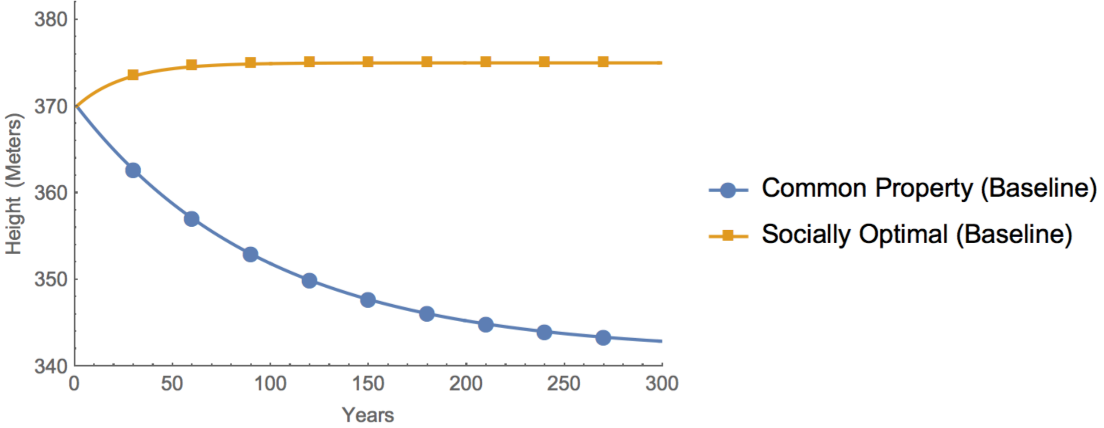
[18] I refer to the results presented in this section as the baseline results. The results of the sensitivity analyses and the tenure simulations presented in the subsections that follow are compared with the baseline results.

Figure 2.1: Dynamics of the Water Table Height

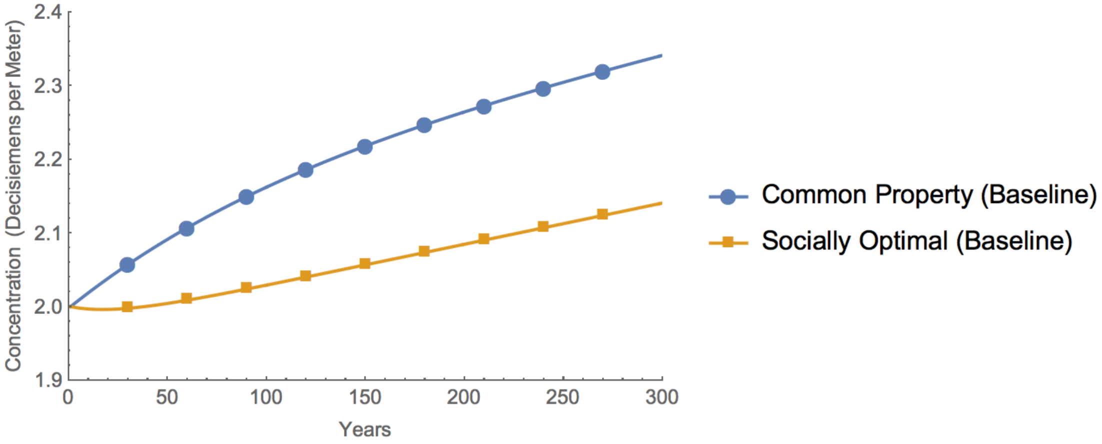


Under optimal management the water table height rises over time and reaches a steady state at the boundary constraint of 375 meters after about 100 years. The groundwater extractions under optimal control are initially less than the steady state level and hence the water table height rises over time.

The dynamics of the groundwater salt concentration are shown in Figure 2.2 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.

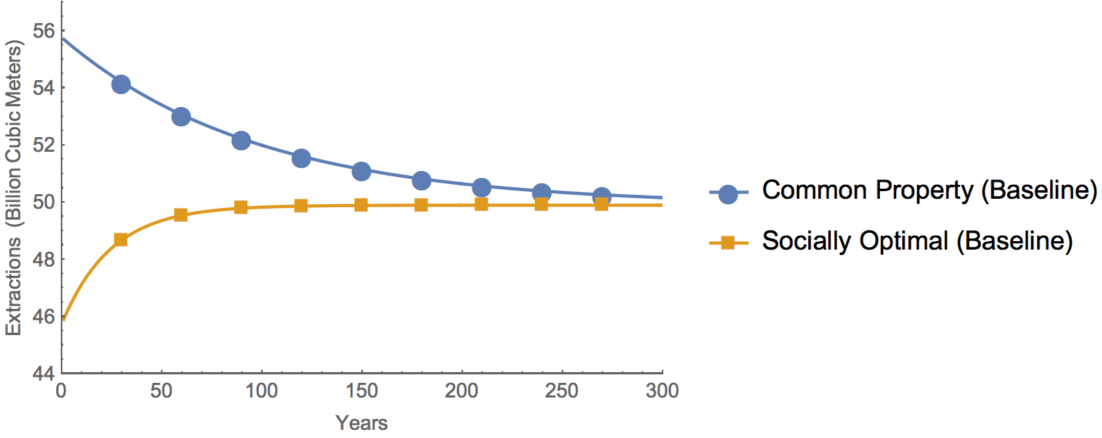
Under optimal management the groundwater salt concentration falls initially as the water table height rises and the volume of groundwater in the aquifer increases. However, after the first 25 years the increase in total salt mass dominates the increase in the volume of groundwater so that the groundwater 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. 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 2.2: Dynamics of the Groundwater Salt Concentration



The long-term trend of groundwater extractions is shown in Figure 2.3 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 2.3: Dynamics of Groundwater Extraction Levels

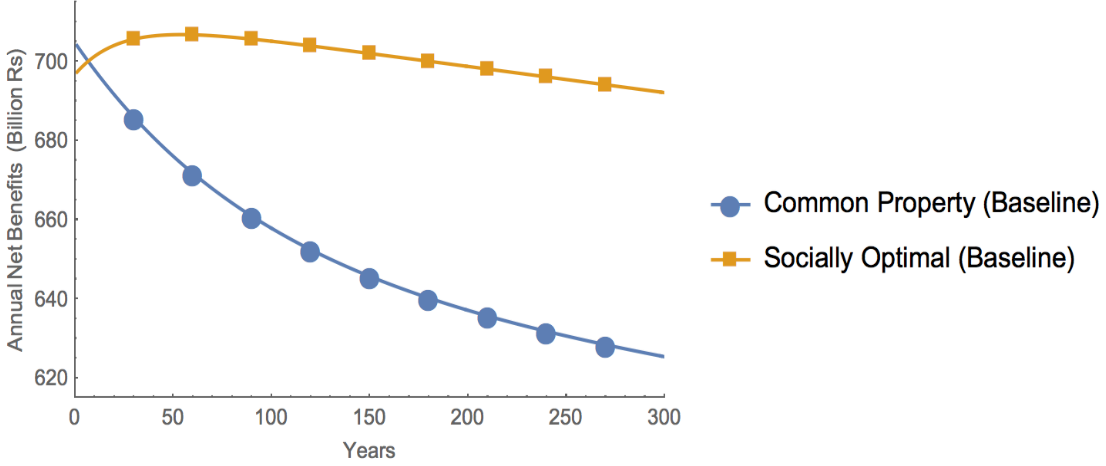


Under optimal management the water table height increases over time since the recharge exceeds the level of extractions. The marginal cost of extraction falls over time and groundwater extractions increase. The extractions reach the steady state after about 100 years. About 95 percent of the adjustment 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 2.4 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 2.4: Dynamics of Annual Net Benefits



2.4.2 Sensitivity Analyses

I now examine the sensitivity of the results to changes in the values of the parameters of the model. I conduct five different sensitivity analyses. In the first two sensitivity analyses I 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 I 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 my model I 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 I 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 me 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 I examine different values of the parameters of the marginal cost and the water demand functions. In sensitivity analysis 4 I 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. I use this case as a lower bound for the variation in the results due to a decrease in the cost of extraction.

Similarly, I 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 I 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:

<u>Sensitivity Analysis 1:</u>

$\beta_{DP} = 0.20$ (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)

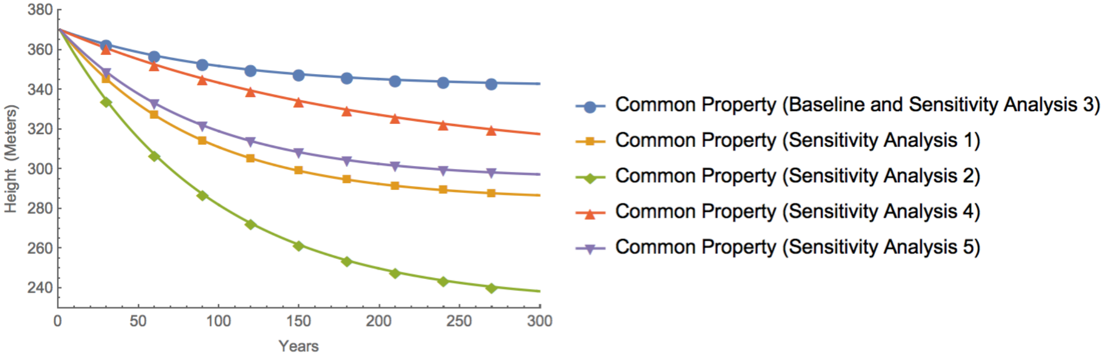
Results of the Sensitivity Analyses

Figures 2.5 and 2.6 below 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.

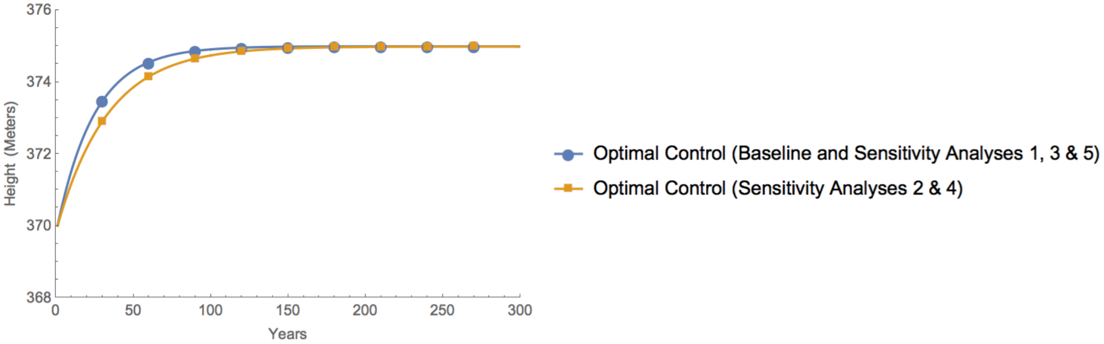
The fall in the water table height under sensitivity analysis 3 (50 percent increase in the salt concentration of surface water) is the same as the fall in the water table height under the baseline model. Since the equation of motion of groundwater quality is independent of groundwater extractions, the 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 2.5: 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 2.6: Dynamics of the Water Table Height Under Optimal Control



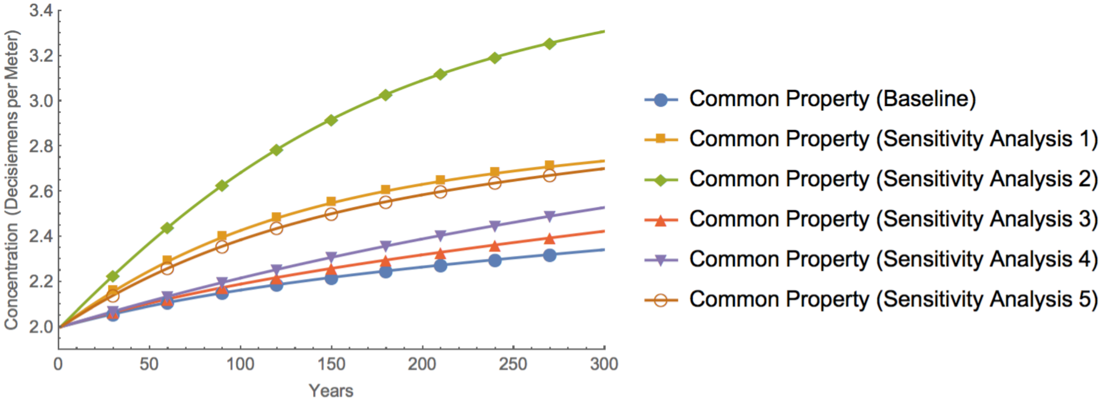
Sensitivity Analysis 1: $\beta_{DP} = 0.20$ (33 percent reduction in the deep percolation coefficient); Sensitivity Analysis 2: $Q_{SW} = 46.95\,Bm^3$ (25 percent reduction in the quantity of surface water under the baseline model); Sensitivity Analysis 3: $c_{sw} = 0.3\,dSm^{-1}$ (50 percent increase 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 results suggest that changes in the parameters of the model do not have a significant effect on the optimal control solution. Policies for optimal control will have a larger impact on the water table height in scenarios that lead to a significant fall in the water table height over time under common property management.

The dynamics of the groundwater salt concentration under the common property regime and under optimal management are shown in Figures 2.7 and 2.8 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}.

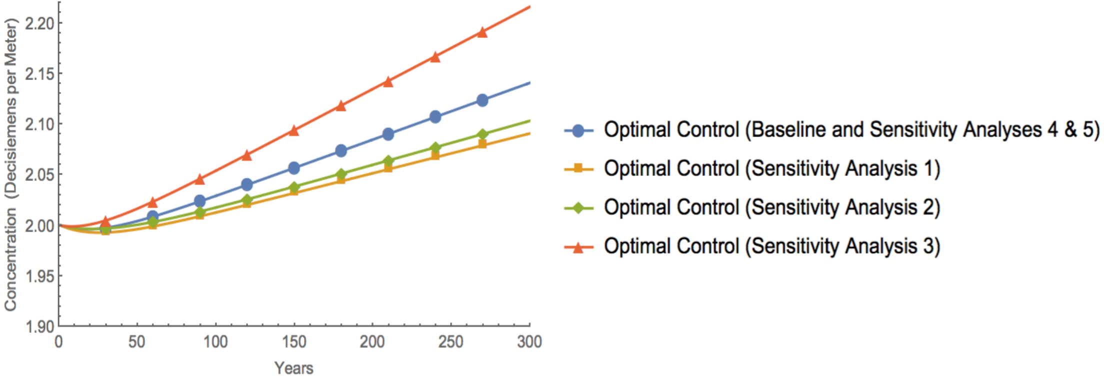
The groundwater salt concentration under sensitivity analyses 2 is greater than the concentration under all the other sensitivity analyses because the reduction in the volume of groundwater under sensitivity analysis 2 is the largest. The groundwater salt concentration under sensitivity analyses 2 is 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 2.7: 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 2.8: 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) under 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.

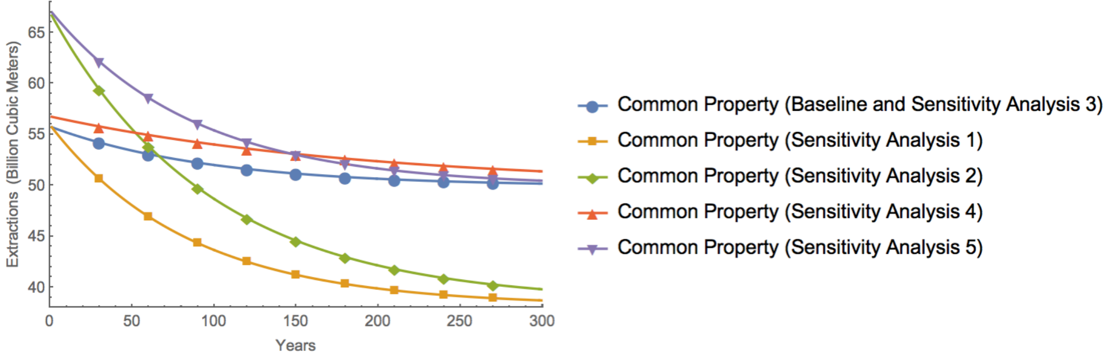
The groundwater salt concentration is the highest under sensitivity analysis 3 and lowest under sensitivity analysis 1 in each year. However, the concentration levels after the first 50 years are between 2.0-2.02 dSm^{-1} under all the sensitivity analyses. For each of the sensitivity analysis, the groundwater 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 2.9 and 2.10 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).

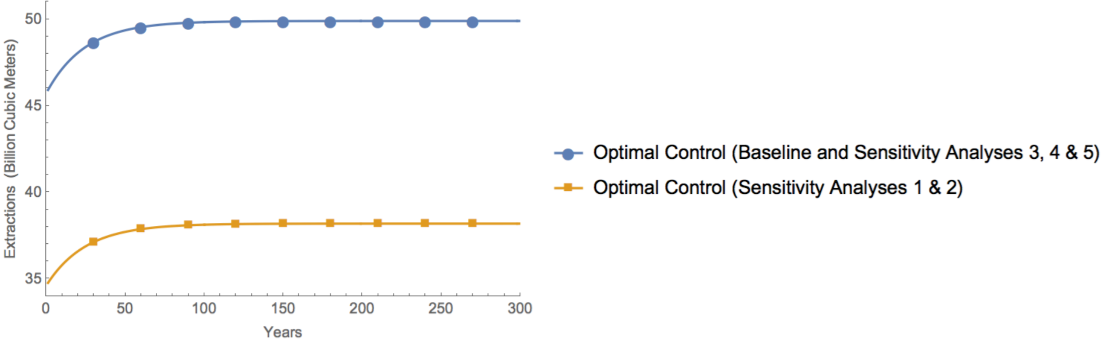
Moreover, in all five sensitivity analyses the initial levels of extractions under optimal management are below the steady state levels. Since extractions depend on the current and future values of the state variables, the lower level of initial extractions implies a higher water table level and better groundwater quality in the future. In all 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 2.9: 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 2.10: 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 2.11 and 2.12 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.[19] 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.

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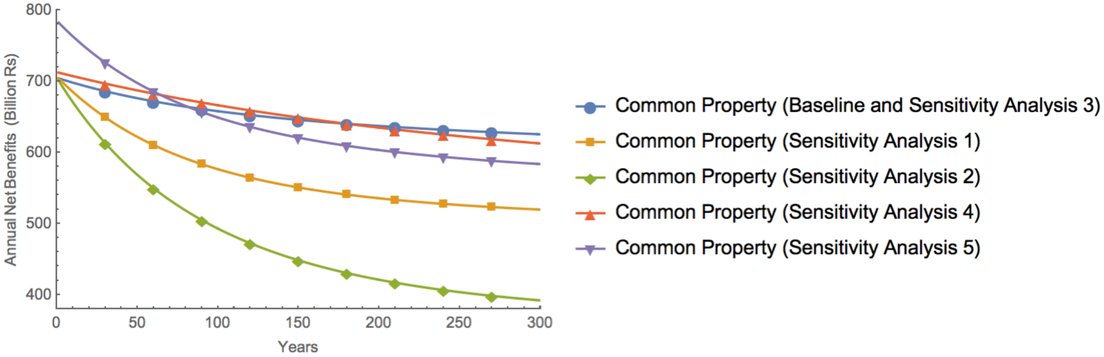
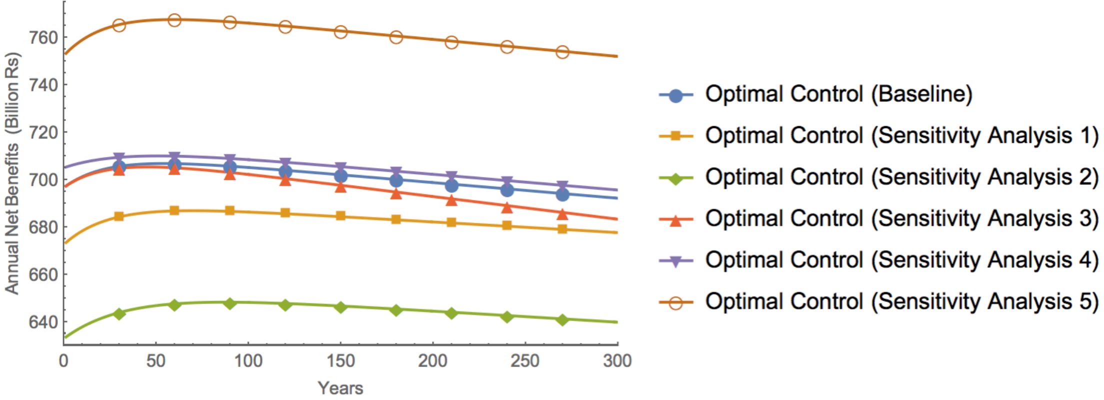
[19] Under common property management the annual net benefits given by sensitivity analysis 3 are slightly less than the annual net benefits given by the baseline model since the impact of salinity on net benefits is higher in sensitivity analysis 3. However, the difference is too small to distinguish between the two in Figure 2.11.

Figure 2.11: 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 2.12: 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 year 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 falls by 12.5 percent for every unit increase in concentration.

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 I have used in my 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 I 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 I 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 I examined the impact of an exogenous shift in the reduced-form water demand function on the dynamics of the state of the aquifer.

2.4.4 Results of the Tenure Model

Figures 2.13 and 2.14 below 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 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.

The marginal user cost of groundwater under the tenure model is almost identical to the marginal user cost under the baseline model since the difference in the water table height given by the two models under common property management is small. The results suggest that differences in tenure are not important in determining the optimal control solution.

Figure 2.13: Dynamics of the Water Table Height Under Common Property

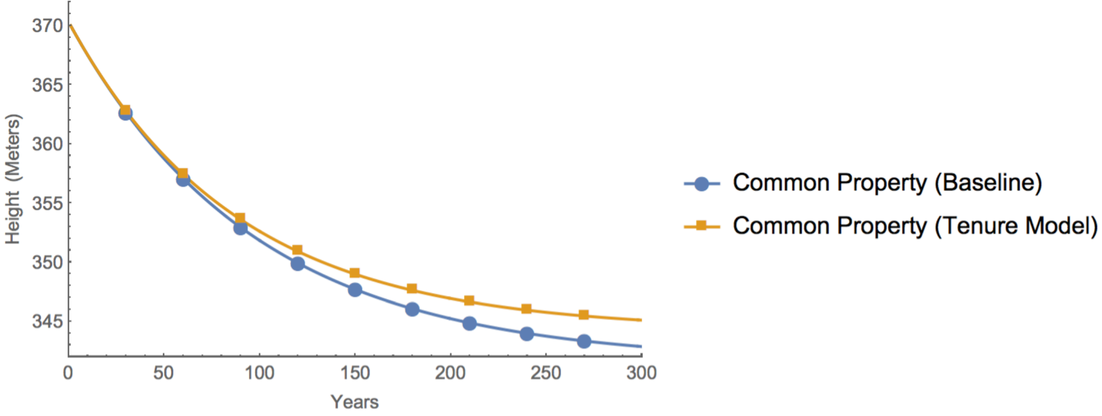
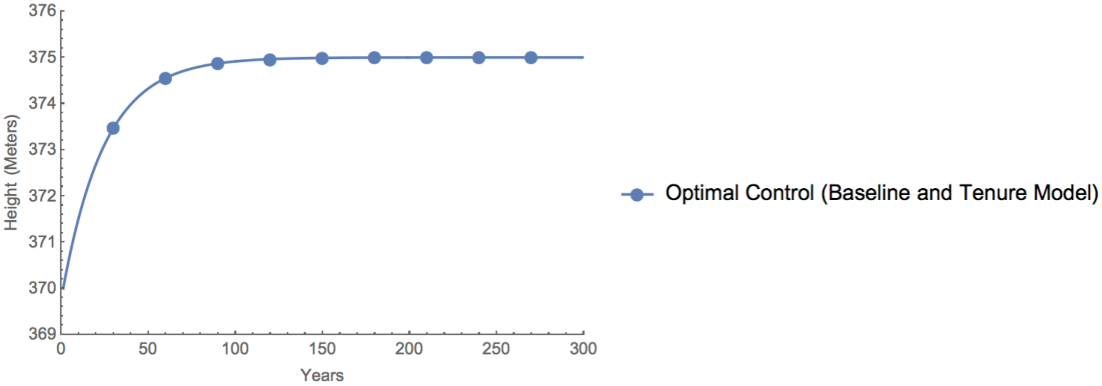


Figure 2.14: Dynamics of the Water Table Height Under Optimal Control



Figures 2.15 and 2.16 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 is 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 the 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 2.15: Dynamics of the Groundwater Salt Concentration Under Common Property

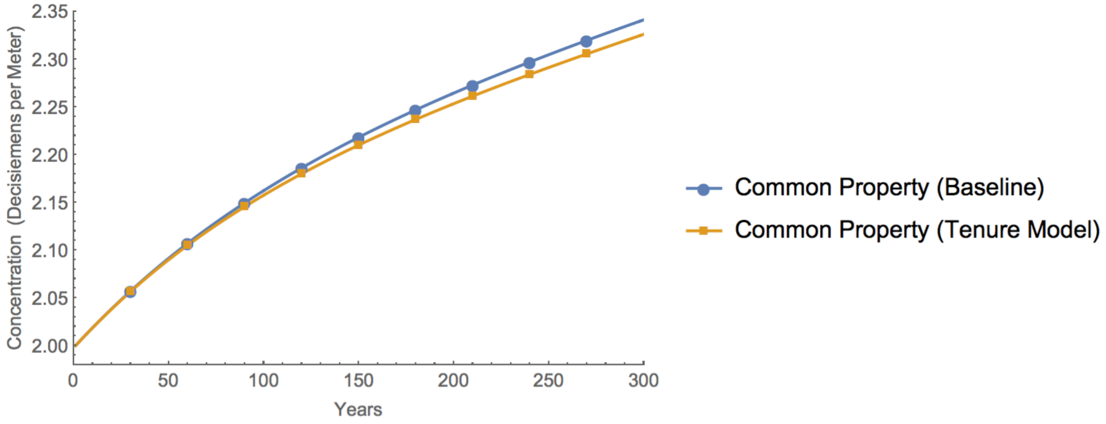
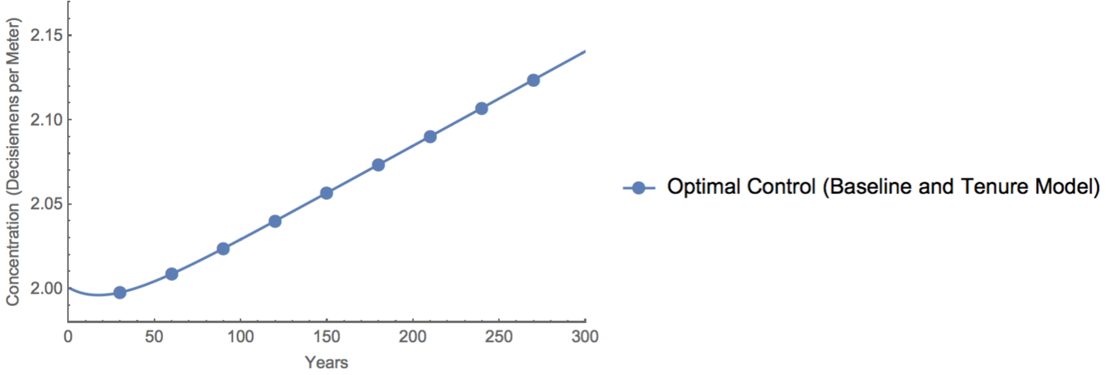


Figure 2.16: Dynamics of the Groundwater Salt Concentration Under Optimal Control



The corresponding groundwater extractions under common property management and under optimal control are show in Figures 2.17 and 2.18 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 2.17: Dynamics of Groundwater Extraction Levels Under Common Property

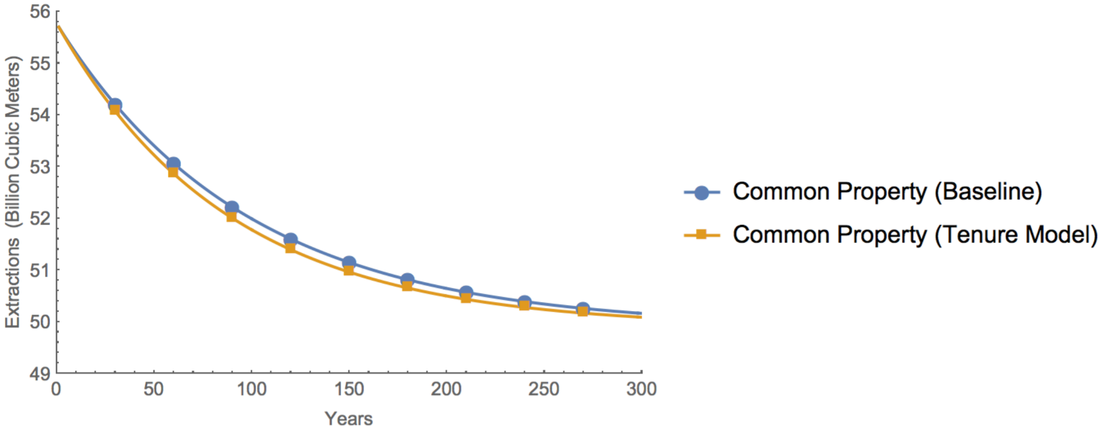
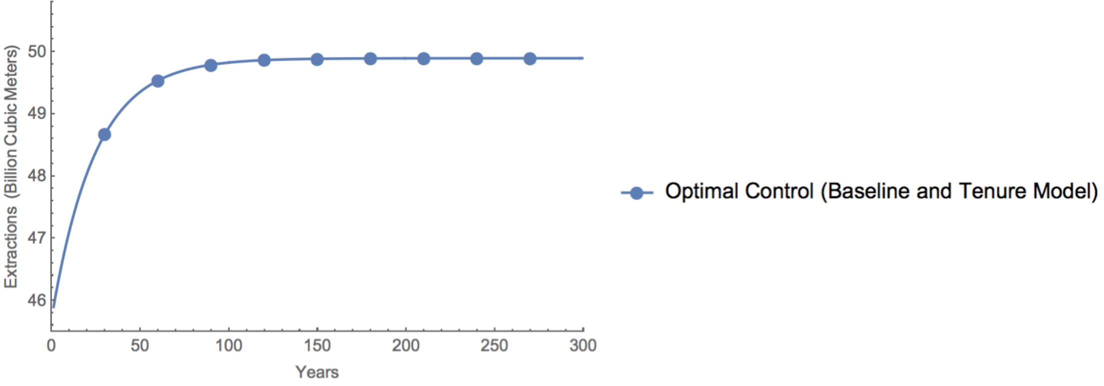


Figure 2.18: Dynamics of Groundwater Extraction Levels Under Optimal Control



The dynamics of the annual net benefits under common property management and under optimal control are presented in Figures 2.19 and 2.20 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 2.19: Dynamics of Annual Net Benefits Under Common Property

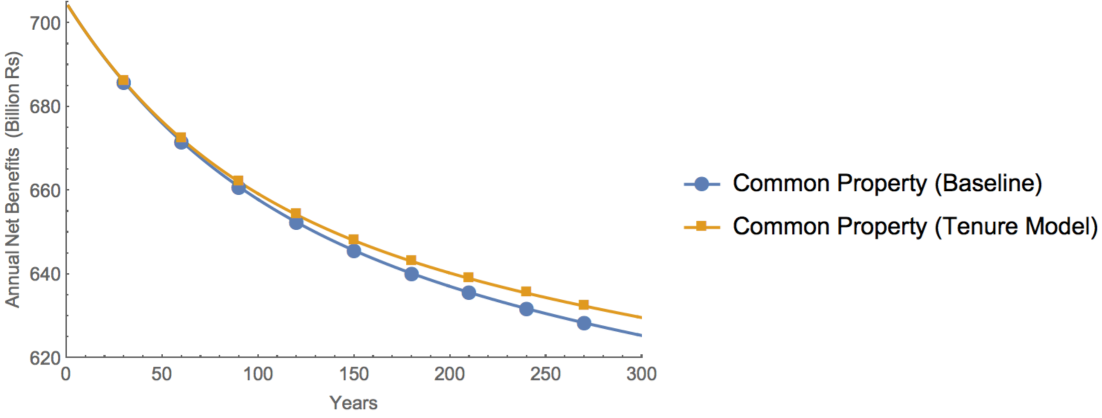
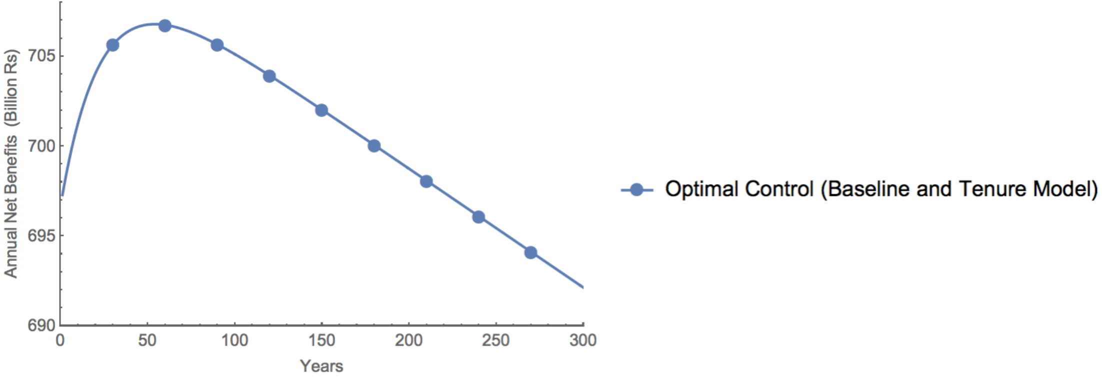


Figure 2.20: Dynamics of Annual Net Benefits Under Optimal Control



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 2.2: 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.

2.5 Policy Instruments and Implications

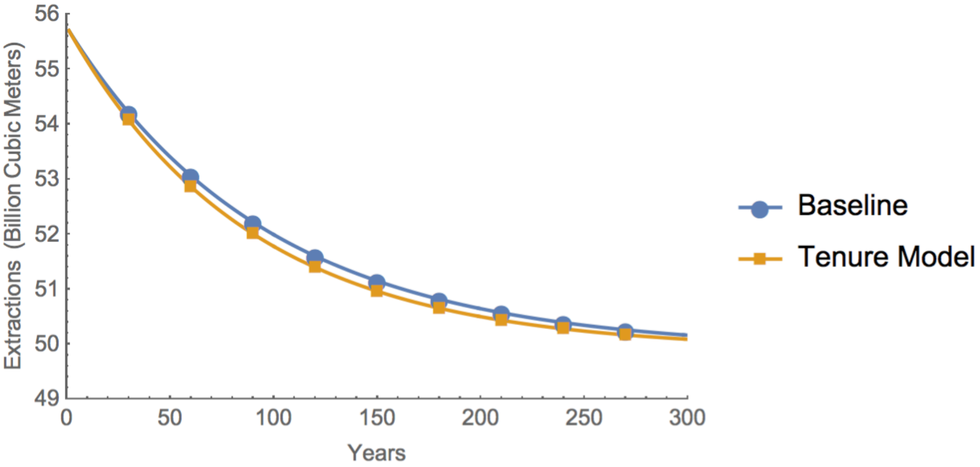
The results in the previous section demonstrate the quantitative benefits associated with optimal management of groundwater in the Indus Basin. However, the results so far do not identify how optimal groundwater extractions can be achieved. Under common property management farmers do not consider the 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 I discuss quantity and price instruments that can lead to the attainment of the optimal levels of the physical and economic variables.

I 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 that 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.

2.5.1 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 2.21 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 2.21: 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 my 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 I examine pricing policies for the optimal management of the aquifer.

2.5.2 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:

$$\pi\left(H_t, K_t, Q_{GW_t}\right) - T_t Q_{GW_t} \tag{2.37}$$

The first-order condition yields:

$$\frac{\partial \pi}{\partial Q_{GW_t}} = T_t \tag{2.38}$$

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 (2.14) a regulator maximizes the following for optimality:

$$\pi\left(H_t, K_t, Q_{GW_t}\right) + \alpha V(H_{t+1}, K_{t+1}) \tag{2.39}$$

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 (2.39) 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:

$$\frac{\partial \pi}{\partial Q_{GW_t}} = \frac{\alpha(1-\beta_{DP})}{AS_y}\frac{\partial V}{\partial H_{t+1}} \tag{2.40}$$

Comparing equations (2.38) and (2.40) shows that the optimal tax is given by:

$$T_t = \frac{\alpha(1-\beta_{DP})}{AS_y}\frac{\partial V}{\partial H_{t+1}} \tag{2.41}$$

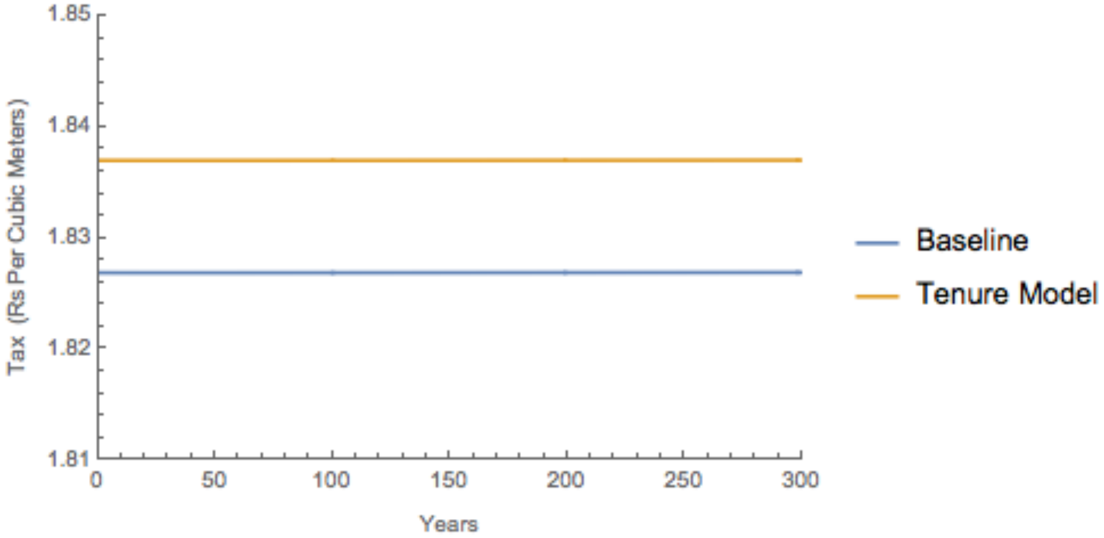
After converting the groundwater salt mass to groundwater salt concentration using equation (2.7) the optimal tax rate can be expressed as:

$$T_t = \frac{\alpha(1-\beta_{DP})}{AS_y}\left[\frac{\partial V}{\partial H_{t+1}} - \frac{c_{GW_t}}{H_t}\frac{\partial V}{\partial c_{GW_{t+1}}}\right] \tag{2.42}$$

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 2.22 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 marginal user cost of groundwater under the tenure model.

Figure 2.22: 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 that 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 onboard various stakeholders 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-users 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.

2.5.3 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 2.21). 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 sub-section. 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 permits 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 I 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.

2.5 Summary and Conclusions

In this chapter I 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.

I 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 my model do not vary across space, the sensitivity analyses allowed me 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.

I 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. I adapted the baseline model to include differences in extractions across owner cultivators and sharecroppers. I 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, I 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.

I 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 I 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 I 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. My 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.

Chapter 3: Simulating the Effects of Water Policies on the Allocative Efficiency of Groundwater and Land Productivity in Pakistan

3.1 Introduction

Water for irrigation has historically been an important input in Pakistan's agricultural sector, but with an increasing population and limited natural sources of fresh water, Pakistan is fast becoming a water-scarce country. The government has not yet adapted water policies to reflect the reality of such future. Increasing unreliability of surface water supplies, disproportionately less amount of surface water at the tail end of watercourses compared to the head end, a falling water table height and deterioration of groundwater quality are some of the main water management issues that Pakistani policy makers have to address (Briscoe and Qamar 2006). However, the lack of a knowledge base has hampered the development of an adaptive water management strategy that incentivizes the sustainable use of water resources. Simulating the efficacy of potential policies is a first step towards informing a dialogue on water policy reform in Pakistan.

Although farmers in Pakistan use surface water as the primary source of irrigation, their reliance on groundwater to meet irrigation shortfalls due to the unreliability of surface water supplies has increased in the last two decades (Qureshi et al. 2004). Groundwater irrigation has helped farmers increase land productivity. Evidence from Pakistan 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). However, a comparison of land productivity with groundwater utilization alone may be misleading, because land productivity also depends on a host of other farm-specific factors such as surface water availability, other agricultural inputs, soil quality, weather conditions, and technical knowledge of farmers.

Groundwater is available in most of the Indus Basin but its utilization differs across farms that are characterized by constraints that include locational and environmental factors (Nasim et al. 2014). Some of the locational and environmental factors that lead farmers in Pakistan to misallocate groundwater are: access to surface irrigation water, location on watercourse, and quality of available groundwater. Differences across these locational and environmental factors explain part of the inefficiency of groundwater utilization in Pakistan and its impact on land productivity.

The unregulated use of groundwater in the region is leading to a depletion of the resource, which will have an adverse impact on land productivity in the future. The irrigated agriculture economy in Pakistan requires policy interventions to ensure the sustainable use of groundwater and to increase land productivity and the livelihood of farmers. Simulating the effects of policy interventions on the efficiency of groundwater utilization and on land productivity requires a systematic approach with simultaneous considerations of other inputs of production and the locational and environmental characteristics of farms.

In this chapter, I use a panel dataset of rural households to examine the effects of two policy interventions—increase access to surface water and increase reliability of surface water supply—on the allocative efficiency of groundwater and on land productivity in Pakistan’s agricultural sector. Increasing access to surface water and increasing the reliability of surface water supply allows farmers to substitute groundwater for surface water, which might improve their utilization of groundwater.

I use location on a watercourse as a proxy for the reliability of surface water supply. Farms at the head and middle of a watercourse draw their allocated share of surface water before it flows further down. Losses due to seepage and water theft prevent farmers at the tail of the watercourse from getting their fair share of surface water (Briscoe and Qamar 2006). The location of farms higher up on a watercourse ensures a more reliable supply of surface water.

I first use stochastic frontier analysis to estimate the effects of a set of covariates—including access to surface water and location on a watercourse—on the allocative efficiency of groundwater. Using the estimation results, I determine which of the policy interventions (increase access to surface water and increase reliability of surface water) improve the allocative efficiency of groundwater. I then simulate the effect of the selected policies on the allocative efficiency of groundwater. I also quantify the effect of the change in the allocative efficiency of groundwater on land productivity.

The estimation strategy in Chapter 1 did not include the effects of a set of covariates on the allocative efficiency of groundwater. The estimation of the effects of a set of covariates on the allocative efficiency of groundwater allows me to conduct the simulations of policy interventions. The analysis in this chapter sheds light on factors that improve the utilization of groundwater and consequently increase land productivity.

This chapter is organized as follows: Section 3.2 reviews the literature on the economic impact of water policy interventions in agriculture. Section 3.3 develops a model of allocative inefficiency and presents the estimation strategy. Section 3.4 discusses the covariates that explain the allocative efficiency of groundwater. Section 3.5 provides the estimation results. Section 3.6 describes the effect of policy simulations on the allocative efficiency of groundwater and land productivity. Section 3.7 concludes.

3.2 Brief Literature Review

Since I provided a general review of the literature on stochastic frontier analysis in Chapter 1, in this section, I restrict attention to some of the studies that simulate the economic effects of water policy interventions in agriculture.

Varela-Ortega et al. (1998) use a dynamic mathematical approach to simulate the effect of different water pricing policies on water demand, farmers' incomes and the revenue collected by water agencies in three river basins in Spain. They find that alternative water pricing policies lead to differences in water demand across regions, which can be explained by the prevailing structural conditions in the agricultural regions. They also show that water pricing alone might not be sufficient to encourage water savings and that pricing policies need to be supplemented by programs designed to modernize the existing water delivery infrastructure.

Volk et al. (2009) simulate the effects of policy instruments such as the support of agro-environmental measures by Europe's Common Agricultural policy and regional landscape development programs on water quality under different land use and management schemes. Their results show that achieving the water quality target of the European Water Framework Directive would require drastic changes in land use, which are unrealistic from a socio-economic point of view.

Reichard (1995) uses an optimization model for groundwater and surface water management to simulate the effect of efficient strategies for meeting water demand and controlling water quality. He applies the model to the Santa Clara-Calleguas Basin in southern California to show that significant reduction in water use or the acquisition of supplemental water is needed to control seawater intrusion in the basin, which deteriorates water quality. He also shows that the artificial groundwater recharge program in the region has helped control seawater intrusion and expanding the program can lead to additional benefits.

Bartolini et al. (2007) show that in Italy, policies such as liberalization of agricultural markets decrease water consumption in agriculture but also decrease land productivity. In comparison, water pricing policies have a lower effect on water use and land productivity. They also show that policies that reduce water consumption also lead to negative economic outcomes, which emphasizes the tradeoff between water sustainability and the livelihood of the agricultural sector.

Riesgo and Gomez-Limon (2006) develop a multi-criteria mathematical programming model to simulate the effect of a combination of agricultural policies and irrigation pricing policies on farm incomes and water conservation in Spain. Their results show that the reforms of the Common Agricultural Policy would have superior economic and environmental outcomes compared to various water pricing scenarios. They conclude that water pricing policies should be subordinate to agricultural policies in order to efficiently meet policy objectives in irrigated regions.

Dixon et al. (2011) use a computable general equilibrium model to simulate the economic effects of an irrigation water buyback scheme in the Southern Murray-Darling Basin. Their results indicate that contrary to the concerns of the local Irrigators' council, an irrigation water buyback policy would enhance economic activity in the region. Though such a policy would increase the price of water substantially, farmers would react by reallocating resources between agricultural activities without loss of income.

Garcia-Vila and Fereres (2012) combine a crop model and an economic optimization model to simulate the effects of a set of water and agricultural policies (removal of crop subsidies) on crop yields. Their results show that changes in cropping patterns under agricultural policies lead to more water savings than an increase in the price of water.

Huang et al. (2008) simulate the effect of water pricing on water demand in China. Their results show that increasing the price of water would curb the demand for water and lead to substantial water savings. However, the increase in irrigation costs would lead to lower production of all crops and reduce the incomes of rural households.

The studies reviewed above suggest that the economic and environmental impact of water policies is region specific. Moreover, many of the studies focus on water pricing policies and do not account for the impact of non-price based policies on the allocative efficiency of groundwater. Using the theory of profit maximization, I examine locational and environmental covariates that might explain the variation in the allocative efficiency of groundwater and then simulate the effect of changes in some of the covariates on the allocative efficiency of groundwater and land productivity. The studies reviewed in this section are based on normative models—these models describe the ideal response of crops and individuals to changes in the parameters of the models. The simulations that I conduct are based on the observed behavioral response of farmers to changes in the variables of the model.

3.3 Modeling Allocative Inefficiency in a Profit Maximization Framework

In the model described below, I depart from the model in Chapter 1 by including the effects of a set of covariates on the allocative efficiency of groundwater. In Chapter 1, the allocative efficiency of groundwater was defined as a time-invariant and producer-specific fixed-effect. In the model below, the allocative efficiency of groundwater is producer-specific, and a function of a set of time variant covariates and a time invariant fixed-effect.

I assume that farmers maximize profit, which is defined over aggregate output and multiple inputs. Technical inefficiency is treated as a producer-specific fixed effect, and the allocative inefficiency of all variable inputs except groundwater as producer- and input-specific fixed-effects.[20] The allocative inefficiency of groundwater is defined as a linear function of time variant covariates and a producer-specific fixed-effect. These covariates affect land productivity indirectly through their effect on the allocative efficiency of groundwater. Since the two period panel dataset used to estimate the model

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[20] This implies that technical inefficiency and allocative inefficiency of all variable inputs except groundwater are invariant across time.

only spans three years, I find it reasonable to treat technical inefficiency and the allocative inefficiency of all variable inputs except groundwater as fixed effects. Defining the allocative inefficiency of groundwater as a function of time variant covariates allows me to simulate the effect of changes in the covariates on allocative inefficiency and, consequently, land productivity.

Treating technical inefficiency, allocative inefficiency of all variable inputs except groundwater, and the unobservable component of the allocative inefficiency of groundwater as time-invariant allows me to estimate the model without making strong distributional assumptions about the inefficiency terms. One drawback of this approach is that the technical inefficiency term will subsume any unobserved time-invariant heterogeneity (Greene 2008). Nonetheless, avoiding strong distributional assumptions about the inefficiency terms is an attractive feature of the model.

I follow Kumbhakar and Lovell (2000), and Kumbhakar and Wang (2006) in deriving a primal profit system. The stochastic production function for a single aggregate output is given by:

$$y_{it} = f(x_{it}, z_{it}) \exp\{v_{it} - u_i\} \quad i = 1, \ldots, I \tag{3.1}$$

where i and t refer to producers and time, x_{it} is a vector of variable inputs, z_{it} is a vector of quasi-fixed inputs, v_{it} is statistical noise, and u_i is output-oriented and time-invariant technical inefficiency (the percentage loss in output due to technical inefficiency).

The first-order conditions for profit maximization imply:[21]

$$f_n \exp\{v_{it} - u_i\} = \frac{w_{nit}}{p_{it}} \exp\{-\xi_{ni}\} \quad n = 1, \ldots, N \tag{3.2}$$

where p_{it} is the output price and w_{nit} is the price of the nth variable input, and ξ_{ni} is the time invariant allocative inefficiency of the nth variable input, excluding groundwater. Allocative inefficiency is defined as the extent to which the first-order condition of profit maximization for the jth input fails to hold.

The Allocative inefficiency of groundwater ξ_{git} is a linear function of a vector of L time variant covariates c_{it} and a producer-specific fixed-effect s_i:

$$\xi_{git} = \sum_l \phi_l c_{it} + s_i \quad l = 1, \ldots, L \tag{3.3}$$

The covariates used to explain allocative efficiency include: the share of total farm area with access to surface water; shares of total farm area located at the head, middle and tail of a watercourse; shares of total farm area that receive good quality and medium quality groundwater; and shares of total farm area with three different types of soil. These variables are explained in greater detail in the next section.

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[21] $Max[py - w'x]$
$s.t. \quad y = f(x)\exp\{v - u\}$

I employ a translog production function which, after dropping the producer subscript i (for convenience), is given by:

$$lny_t =$$
$$\beta_0 + \sum_n \beta_n lnx_{nt} + \sum_q \gamma_q lnz_{qt} + \frac{1}{2}\left[\sum_n \sum_k \beta_{nk} lnx_{nt} lnx_{kt}\right] + \frac{1}{2}\left[\sum_q \sum_r \gamma_{qrt} lnz_{qt} lnz_{rt}\right] +$$
$$\sum_n \sum_q \delta_{nq} lnx_{nt} lnz_{qt} + v_t - u \tag{3.4}$$

Using equations (3.2), (3.3) and (3.4), I derive the input demand equations in (3.5). Since the production function is translog, the input demand equations in (3.5) are not in closed form.

$$lnx_{nt} = lny_{t|v=0} - ln\frac{w_{nt}}{p_t} + \ln\left[\beta_n + \sum_k \beta_{nk} lnx_{kt} + \sum_q \delta_{nq} lnz_{qt}\right] + \xi_n \tag{3.5}$$

The input demand equation for groundwater takes the same form as the equation in (3.5), except the allocative efficiency of groundwater is time variant as defined by equation (3.3). I eliminate the time invariant terms β_0, u, ξ_n and s by first differencing equations (3.4) and (3.5). After adding a stochastic noise term to each of the input demand equations, the system of equations can be estimated using iterated nonlinear seemingly unrelated regression (INLSUR).

After estimating the parameters, the intercept β_0 can be calculated using the following normalization:

$$\widehat{\beta_0} = \max(\bar{e}) \tag{3.6}$$

where the $\bar{e}$ is the temporal mean of the residuals of equation (3.4).

After calculating $\widehat{\beta_0}$, I follow Kumbhakar and Lovell (2000) in calculating the fixed effects u, ξ_n and s by means of:

$$\hat{u} = \widehat{\beta_0} - \bar{e} \tag{3.7}$$

$$\widehat{\xi_n} = \overline{lnx_{nt}} - \overline{lny_{t|v=0}} + \overline{ln\frac{w_{nt}}{p_t}} - \overline{\ln\left[\beta_n + \sum_k \beta_{nk} lnx_{kt} + \sum_q \delta_{nq} lnz_{qt}\right]} \tag{3.8}$$

$$\hat{s} = \overline{lnx_{gt}} - \overline{lny_{t|v=0}} + \overline{ln\frac{w_{gt}}{p_t}} - \overline{\ln\left[\beta_n + \sum_k \beta_{nk} lnx_{kt} + \sum_q \delta_{nq} lnz_{qt}\right]} - \sum_l \overline{\phi_l c_{lt}} \tag{3.9}$$

where a bar over a term represents its temporal mean and the subscript g distinguishes groundwater from other variable inputs.

I estimate the model using data from the Pakistan Rural Household Survey panel dataset.

3.4 Data Sources and Description

For a detailed description of the two datasets—Pakistan Rural Household Survey I (PRHS-I) and Pakistan Rural Household Survey II (PRHS-II)—and the variables used in the analysis, I refer the reader to Chapter 1. Below I describe the set of covariates that I use to explain the allocative efficiency of groundwater.

As mentioned earlier, the allocative efficiency of groundwater is defined as a linear function of time variant covariates and a producer-specific fixed-effect. The time variant covariates are shares of environmental and locational characteristics of plots in total household farm area. These include the shares of total farm area with and without access to surface water, the shares of total farm area at the head, middle and tail of a watercourse, the shares of total farm area that receives good quality, medium quality and poor quality groundwater, and shares of total farm area with four types of soil (clay, sandy, maira and chikni).[22]

In Chapter 1, I used the same dataset to show that most farms over utilize groundwater. I also showed that while farms with access to surface water and farms without access to surface water over utilize groundwater, farm without access to surface water tend to utilize more groundwater compared to farms with access to surface. Similarly, I showed that farms at the head, middle and tail of a watercourse all tend to over utilize groundwater. Farms at the tail of the watercourse tend to utilize more groundwater compared to farms at the head of a watercourse and farms at the middle of a watercourse.

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[22] Maira and chikni are local terms for sandy loam soil and loam soil respectively.

In Chapter 1, I included the locational and environmental characteristics of farms as variables to control for farm-level heterogeneity in the production function. I depart from that method by including the locational and environmental characteristics of farms as covariates that affect the allocative efficiency of groundwater. This estimation strategy also allows me to simulate the effect of changes in the covariates on the allocative efficiency of groundwater and, consequently, on land productivity.

Given the fixed allocations of surface water, and its unreliability, farms with access to surface water might not meet their irrigation requirements with surface water alone. These farms might use groundwater to meet possible irrigation deficits. However, farms with only groundwater do not have any additional source of irrigation to meet their water requirements. Hence, these farms might over utilize groundwater.

Location on a watercourse is a proxy for the reliability of surface water supply. Farms located at the head and middle of a watercourse get access to surface water before farms located at the tail of the watercourse. Since the allocation of surface water is uniform (fixed per unit of land) across all locations of a watercourse, farms located at the tail of a watercourse are at a disadvantage given the unreliable supply of surface water. Farms at the tail of a watercourse might over utilize groundwater to compensate for the shortfall in the supply of surface water.

The quality of groundwater that is available for irrigation might also affect the utilization of groundwater. Good quality groundwater relative to saline groundwater is beneficial for crop production and the application of good quality groundwater can lead to higher land productivity. Farms might over utilize good quality groundwater, especially if it is scarce.

The utilization of groundwater might also differ across soil type owing to the water retention property of each type of soil (Zhang 2010). Farms with soil that retains less water might have to be irrigated more compared to farms with soil that has a relatively higher water retention rate. Variation in soil type might be important in explaining differences in the allocative efficiency of groundwater.

I suspect that the share of total farm area with access to surface water and the shares of total farm area at the head, middle and tail of a watercourse are highly collinear since location on a watercourse guarantees access to surface water. The PRHS dataset shows that all farms that are located on a watercourse also have access to surface water. To avoid the problem of collinearity, I estimate two models: Model I includes all the covariates of the allocative efficiency of groundwater except the shares of total farm area at the head, middle and tail of a watercourse. This model captures the effect of access to surface water on the allocative efficiency of groundwater. Model II includes all the covariates of the allocative efficiency of groundwater except the share of total farm area with access to surface water. In Model II, the shares of total farm area at the head, middle and tail of a watercourse are a proxy for both access to surface water and the reliability of surface water supply.

Since the shares of variables in each category add up to 100 percent, I exclude the following variables from the estimation: share of total farm area without access to surface water, share of total farm area not on a watercourse, the share of total farm area that receives poor quality groundwater and the share of total farm area with chikni soil. The share of total farm area that is not on a watercourse equals the share of total farm area without access to surface water.

Table 3.1 provides summary statistics of output, variable inputs, quasi-fixed inputs, and the covariates of the allocative efficiency of groundwater. In the table, I have normalized the output quantity index by the mean output index price to get a measure of crop revenue per hectare. I also report hired labor in number of days so that it can be compared with own farm labor.

Table 3.1: Summary Statistics of the Variables in the Stochastic Profit System

	Mean	Median	St. Dev.	Min	Max
Output, Variable Inputs and Quasi-fixed Inputs					
Output (index Rs./ha)	20181.38	16535.91	16217.12	131.18	132813.40
Hired Labor (days)	23.68	0.00	66.55	0.00	937.75
Fertilizer (index Rs./ha)	3669.66	3047.61	2842.79	0.00	18701.28
Groundwater (hours/ha)	39.88	10.59	68.34	0.00	513.22
Own Male Labor (days/ha)	47.81	29.55	52.47	0.00	297.53
Own Female Labor (days/ha)	11.27	2.20	18.91	0.00	137.14
Capital (index Rs./ha)	3284.13	2533.88	2939.60	0.00	24074.29
Surface Water (Rs./ha)	204.53	66.64	289.16	0.00	1853.29
Covariates of the Allocative Efficiency of Groundwater					
Surface Water (% area)	63.72	100.00	47.92	0.00	100.00
Head of Watercourse (% area)	15.03	0.00	34.17	0.00	100.00
Middle of Watercourse (% area)	28.14	0.00	43.06	0.00	100.00
Tail of Watercourse (% area)	33.77	0.00	45.49	0.00	100.00
Good-Quality Groundwater (% area)	45.67	0.00	49.56	0.00	100.00
Medium-Quality Groundwater (% area)	11.07	0.00	31.16	0.00	100.00
Clay Soil (% area)	20.89	0.00	40.06	0.00	100.00
Sandy Soil (% area)	19.82	0.00	38.13	0.00	100.00
Maira Soil (% area)	32.07	0.00	45.45	0.00	100.00

Note: Descriptive statistics calculated from 1764 observations.

3.5 Estimation Results

As mentioned earlier, to avoid the problem of collinearity between the share of total farm area with access to surface water and the shares of total farm area located at the head, middle and tail of a watercourse, I estimate two models: Model I includes all the covariates of the allocative efficiency of groundwater except the shares of total farm area at the head, middle and tail of a watercourse; Model II includes all the covariates of the allocative efficiency of groundwater except the share of total farm area with access to surface water.

Table 3.2 below shows the descriptive statistics of the allocative efficiency of groundwater estimated under Model I and Model II. The mean and median values of the allocative efficiency of groundwater under both models are positive, which implies that farms tend to over utilize groundwater. The mean and median values of the allocative efficiency of groundwater under Model I are larger than the mean and median values of the allocative efficiency of groundwater under Model II.

Under both models only one farm in the sample has a negative value for the allocative efficiency of groundwater. In Chapter 1, the distribution of the allocative efficiency of groundwater showed that 38 percent of farms underutilized groundwater (negative value for the allocative efficiency of groundwater). Including the time variant covariates of allocative efficiency changes the distribution of the allocative efficiency of groundwater observed in Chapter 1 so that almost all farms over utilize groundwater. However, the mean and median values of the allocative efficiency of groundwater in Chapter 1 were also positive. The inclusion of the time variant covariates of allocative efficiency does not change the result that the majority of the farms in the sample over utilize groundwater.

Table 3.2: Estimates of the Allocative Efficiency of Groundwater

	Mean	Median	Min	Max
Model I				
Allocative Efficiency of Groundwater	2.53 (0.02)	2.55	-0.05	6.29
Model II				
Allocative Efficiency of Groundwater	2.51 (0.02)	2.52	-0.07	6.23

Note: Standard errors of the means in parentheses.

Model I includes: share of total farm area with access to surface water; shares of total farm area with good and medium quality groundwater; shares of total farm area with clay, sandy and maira soil.

Model II includes: shares of total farm area located at the head, middle and tail of a watercourse; shares of total farm area that receives good and medium quality groundwater; shares of total farm area with clay, sandy and maira soil.

The excluded categories in Model I are: share of total farm area without access to surface water; share of total farm area with poor quality groundwater; share of total farm area with chikni soil.

The excluded categories in Model II are: share of total farm area not on a watercourse; share of total farm area with poor quality groundwater; share of total farm area with chikni soil.

The results for the allocative efficiency of groundwater are for farms in the sample that utilize groundwater.

Allocative efficiency of groundwater is unitless and so its magnitude cannot be determined. In Table 3.3 below, I report the descriptive statistics of land productivity for farms that utilize groundwater with the current estimates of the allocative efficiency of groundwater and land productivity when groundwater is efficiently allocated ($\xi_{git} = 0$). I first obtain the distribution of output per hectare by solving the system of equations given by (3.4) and (3.5) simultaneously and using the estimated values of the parameters, technical efficiency and the allocative efficiency of groundwater. Since output per hectare is an index, I weight it by the mean value of the output price index to get a measure of land productivity.

Table 3.3 shows that on average land productivity is higher when groundwater is allocated efficiently on farms (Rs 24649.81 per hectare compared to Rs 23294.22 per hectare under Model I and Rs 24671.45 per hectare compared to Rs 23289.01 under Model II). Under both Model I and Model II, the mean and median values of land productivity in the absence of allocative inefficiency of groundwater are about 6 percent larger than the mean and median values of land productivity in the presence of allocative inefficiency of groundwater. The results emphasize the positive effect of an improvement in the allocative efficiency on land productivity.

Table 3.3: Land Productivity With Efficient and Observed Allocation of Groundwater (Rs per Hectare)

	Mean	Median	Min	Max
Model I				
Land Productivity (With Efficient Allocation of Groundwater)	24649.81 (525.30)	19199.67	247.29	305182.40
Land Productivity (With Observed Allocation of Groundwater)	23294.22 (494.50)	18125.50	255.53	287140.00
Model II				
Land Productivity (With Efficient Allocation of Groundwater)	24671.45 (524.14)	19229.47	249.09	303765.40
Land Productivity (With Observed Allocation of Groundwater)	23289.01 (493.18)	18103.71	256.94	285582.30

Note: Standard errors of the means in parentheses.

Model I includes: share of total farm area with access to surface water; shares of total farm area with good and medium quality groundwater; shares of total farm area with clay, sandy and maira soil.

Model II includes: shares of total farm area located at the head, middle and tail of a watercourse; shares of total farm area that receives good and medium quality groundwater; shares of total farm area with clay, sandy and maira soil.

The excluded categories in Model I are: share of total farm area without access to surface water; share of total farm area with poor quality groundwater; share of total farm area with chikni soil.

The excluded categories in Model II are: share of total farm area not on a watercourse; share of total farm area with poor quality groundwater; share of total farm area with chikni soil.

The results for the allocative efficiency of groundwater are for farms in the sample that utilize groundwater.

The estimated parameters of the locational and environmental covariates of the allocative efficiency of groundwater are given in Table 3.4. I report the parameter estimates for different specifications to test for the robustness of the results. There are three specifications (1, 2 and 3) for Model I and three specifications (4, 5 and 6) for Model II. I estimated the allocative efficiency of groundwater (Table 3.2) and its impact on land productivity (Table 3.3) using specification 1 for Model I and specification 4 for Model II.

The results of Model I show that access to surface water reduces the value of the allocative inefficiency of groundwater. If farms over utilize groundwater, then access to surface water would make these farms allocate groundwater more efficiently compared to farms that do not have access to surface water. The magnitude of the effect of access to surface water remains about the same in specifications 1 and 3, and is slightly larger in specification 2. The effect of access to surface water is statistically significant in all three specifications. The statistical precision of the effect of access to surface water decreases when the effect of the groundwater quality variables is removed (specification 3).

The results of Model II show that being located at the head, middle or tail of a watercourse decreases allocative inefficiency of groundwater. Since being located at the head, middle or tail of a watercourse guarantees access to surface water, the effects of being located at the head, middle or tail of a watercourse on the allocative efficiency of groundwater have the same sign (negative) as the effect of access to surface water on the allocative efficiency of groundwater in Model I.

However, the effect of being located at the tail of a watercourse appears to be larger than the effect of being located at the head of a watercourse in all three specifications. The effect of being located at the middle of a watercourse appears to be larger than the effect of being located at the head of a watercourse and the effect of being located at the tail of a watercourse. I test to see if the effects of being located at the head, middle and tail of a watercourse are statistically different from each other. The values of the χ^2 test statistic are: 1.12 (specification 4); 1.10 (specification 5); 0.43 (specification 6), which are less than the critical values at 10 percent level of significance. Therefore, I fail to reject the null hypothesis that the effects of being located at the head, middle and tail of a watercourse are equal. The results of Model II suggest that reliability of surface water supply (as measured by being located higher up on a watercourse) does not appear to explain the allocative efficiency of groundwater. However, these results confirm the negative effect of access to surface water on the overutilization of groundwater.

The effects of being located at the head, middle and tail of a watercourse are statistically significant in specifications 4 and 5. When the effect of groundwater quality is removed (specification 6), the magnitudes of the effects of being located at the head, middle or tail of a watercourse fall and lose their statistical precision—the effect of being located at the head of the watercourse is not statistically different from zero in specification 6. I test to see if the effects of being located at the head, middle and tail of a watercourse are jointly equal to zero in specification 6. The value of the χ^2 test statistic is 6.01, which is less than the critical value at 10 percent level of significance. Therefore, I fail to reject the null hypothesis that the effects of being located at the head, middle and tail of a watercourse in specification 6 are jointly equal to zero. These results suggest that specification 6 suffers from omitted variable bias due to the exclusion of the groundwater quality variables.

Having access to good quality and medium quality groundwater increases the over utilization of groundwater on farms compared to having access to poor quality groundwater. The statistical significance of the effects of groundwater quality variables is robust under the different specifications. The effects of clay soil and sandy soil are not statistically significant in any of the specifications. In specifications 3 and 6, which exclude the effects of the groundwater quality variables, the effect of maira soil is statistically significant and is positive. These results further confirm the problem of collinearity observed in specifications 3 and 6.

The results imply that increasing the share of land with access to surface water and increasing the share of land located at the head, middle or tail of a watercourse leads to a reduction in the over utilization of groundwater. Location on a watercourse is a proxy for both access to surface water and the reliability of surface water supply. The effects of being located at the head, middle and tail of a watercourse on the overutilization of groundwater are negative. But these effects are not statistically different from each other. The results do not provide evidence to support the hypothesis that a more reliable supply of surface water (as measured by being located higher up on a watercourse) improves the allocative efficiency of groundwater.

The statistical precision of the effects of access to surface water and being located at the head, middle and tail of a watercourse differ across specifications. The results also show that increasing the share of land under good and medium quality groundwater has a positive effect on the over utilization of groundwater.

Table 3.4: Estimates of the Effect of Locational and Environmental Variables on the Allocative Efficiency of Groundwater

	Model I			*Model II*		
	(1)	(2)	(3)	(4)	(5)	(6)
Surface Water (% area)	-0.0014*** (0.0005)	-0.0018*** (0.0004)	-0.0012** (0.0005)			
Head of Watercourse (% area)				-0.0018** (0.0009)	-0.0019** (0.0008)	-0.0009 (0.0008)
Middle of Watercourse (% area)				-0.0027*** (0.0007)	-0.0028*** (0.0006)	-0.0015** (0.0007)
Tail of Watercourse (% area)				-0.0020*** (0.0007)	-0.0021*** (0.0006)	-0.0013* (0.0007)
Good-Quality Groundwater (% area)	0.0036*** (0.0006)	0.0033*** (0.0005)		0.0041*** (0.0006)	0.0041*** (0.0005)	
Medium-Quality Groundwater (% area)	0.0058*** (0.0010)	0.0057*** (0.0010)		0.0062*** (0.0010)	0.0062*** (0.0010)	
Clay Soil (% area)	-0.0010 (0.0007)		0.0007 (0.0007)	-0.0004 (0.0007)		0.0010 (0.0007)
Sandy Soil (% area)	-0.00090 (0.0008)		0.0006 (0.0008)	-0.0004 (0.0008)		0.0008 (0.0008)
Maira Soil (% area)	-0.0002 (0.0007)		0.0023*** (0.0006)	0.0002 (0.0007)		0.0025*** (0.0006)

Note: Standard errors in parentheses.

Wald test for differences in the effects of the shares of total farm area located at the head, middle and tail of a watercourse:

H_0: Head of Watercourse = Middle of Watercourse = Tail of Watercourse

H_A: Head of Watercourse ≠ Middle of Watercourse ≠ Tail of Watercourse

χ^2: 1.12 (specification 4); 1.10 (specification 5); 0.43 (specification 6)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The estimated effects of the locational and environmental characteristics of farms on the allocative efficiency of groundwater suggest that increasing access to surface water might be a potential policy that could improve the utilization of groundwater. In the next section I use the estimated parameter values from Model I to simulate the effect of marginal increases in the share of total farm area with access to surface water on the allocative efficiency of groundwater and land productivity.

3.6 Policy Simulations

3.6.1 Description of the Simulations

In the last section I demonstrated that increasing access to surface water decreases the over utilization of groundwater. This leads to a more efficient allocation of groundwater on farms and better allocative efficiency, in turn, increases land productivity. I also showed that being located at the head, middle or tail of a watercourse has a negative effect on the overutilization of groundwater. However, the effects of being located at the head, middle and tail of a watercourse were not statistically different from each other. The results suggested that access to surface water improves the allocation of groundwater while reliability of surface water supply (as measured by being located higher up on a watercourse) does not appear to explain the allocative efficiency of groundwater.

In this section I simulate the effect of marginal increases in the share of total farm area with access to surface water—a policy that might be relevant for the region—on the allocative efficiency of groundwater and land productivity. I increase the share of total farm area with access to surface water for farms that already have access to surface water and farms that do not have access to surface water. I use the estimated parameters from Model I (specification 1) to conduct the simulations. Since the focus of the simulations is on the use of groundwater, the statistics and results reported in this section are based on the farms in the sample that utilize groundwater (1007 farms).

I conduct a total of four simulations. In the first four simulations I add vectors of at most 10, 25, 50 and 100 percent, respectively, to the share of total farm area with access to surface water. I ensure that the values of the shares, after adding the vectors, do not exceed 100 percent in any of the simulations—farms that have a share of total farm area with access to surface water equal to 100 percent are not affected by the addition of the vectors. The last simulation (addition of a vector of at most 100 percent to the share of total farm area with access to surface water) shows the maximum overall effect of increasing access to surface water on the allocative efficiency of groundwater and land productivity.

Using each of the simulation vectors I recalculate the allocative efficiency of groundwater by means of equation (3.3), which I then use to derive the value of output per hectare for each farm by solving the system of equations in (3.4) and (3.5) simultaneously. I report a measure of land productivity by weighting the simulated values of output per hectare by the mean value of the output price index. Table 3.5 below summarizes each of the simulations:

Table 3.5: Description of Simulations

Simulation 1	Add at most 10 percent to the share of total farm area with access to surface water.
Simulation 2	Add at most 25 percent to the share of total farm area with access to surface water.
Simulation 3	Add at most 50 percent to the share of total farm area with access to surface water.
Simulation 4	Add at most 100 percent to the share of total farm area with access to surface water.

For the four simulations, Table 3.6 provides the summary statistics of the share of total farm area with access to surface water. Simulations with larger mean and median values of the share of total farm area with access to surface water will have a greater effect on the allocative efficiency of groundwater and land productivity.

Table 3.6: Summary Statistics of the Simulation Variables

	Mean	Median	St. Dev.	Min	Max
Surface Water (% area)	63.72	100.00	47.92	0.00	100.00
Simulation1: Surface Water (plus 10 %)	67.39	100.00	43.13	10.00	100.00
Simulation2: Surface Water (plus 25 %)	72.88	100.00	35.94	25.00	100.00
Simulation 3: Surface Water (plus 50 %)	81.99	100.00	23.96	50.00	100.00
Simulation 4: Surface Water (plus 100 %)	100.00	100.00	0.00	100.00	100.00

Note: The statistics are for farms in the sample that utilize groundwater.

3.6.2 Simulation Results

Table 3.7 below shows the distribution of the allocative efficiency of groundwater under each of the simulations. Baseline refers to the results obtained using the observed values of the share of total farm area with access to surface water. The simulated distributions of the allocative efficiency of groundwater show that increasing the share of total farm area with access to surface water leads to less over utilization of groundwater compared to the baseline result. The mean value of the allocative efficiency of groundwater under each of the simulations is statistically lower than the mean value of the allocative efficiency of groundwater under the baseline model. However, allocative efficiency is unitless and the differences in the allocative efficiency of groundwater under each of the simulations cannot be sufficiently compared. To quantify the overall effect of the simulations I turn to the distribution of land productivity.

Table 3.7: Overall Effect of Increasing the Share of Total Farm Area with Access to Surface Water on the Allocative Efficiency of Groundwater

	Mean	Median	Min	Max
Baseline	2.53 (0.02)	2.55	-0.05	6.29
Simulation1: Surface Water (plus 10 %)	2.53^{***} (0.02)	2.54	-0.05	6.27
Simulation2: Surface Water (plus 25 %)	2.52^{***} (0.02)	2.53	-0.05	6.25
Simulation 3: Surface Water (plus 50 %)	2.50^{***} (0.02)	2.51	-0.05	6.22
Simulation 4: Surface Water (plus 100 %)	2.46^{***} (0.02)	2.47	-0.05	6.15

Note: Standard errors of the means in parentheses.

H_0: mean (simulation) $=$ mean (baseline)

H_A: mean (simulation) $<$ mean (baseline)

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

The results for the allocative efficiency of groundwater are for farms in the sample that utilize groundwater.

Table 3.8 below shows the indirect effect of the simulations (through improvements in the allocative efficiency of groundwater) on land productivity. The results show that land productivity increases as the share of total farm area with access to surface water rises. Land productivity increases as the allocative efficiency of groundwater improves under each of the simulations.

However, the increase in land productivity under all the simulations is modest at best. The largest increase in land productivity is under simulation 4—a 0.1 percent increase in the mean and median values of land productivity, respectively, under the baseline due to a 36 percent increase in the mean value of the share of total farm area with access to surface water. Given that land productivity when groundwater is efficiently allocated is about 6 percent greater than land productivity under the baseline result, increasing the share of total farm area with access to surface water is inadequate to recover the losses in land productivity due to the over utilization of groundwater.

Table 3.8: Overall effect of Increasing the Share of Total Farm Area with Access to Surface Water on Land Productivity (Rs per Hectare)

	Mean	*Percent Change in the Mean Value*[a]	Median	Min	Max
Baseline (With Efficient Allocation of Groundwater)	24649.81 (525.30)	5.50	19199.67	247.29	305182.40
Baseline (With Observed Allocation of Groundwater)	23294.22 (494.50)		18125.50	255.53	287140.00
Simulation1: Surface Water (plus 10 %)	23297.05*** (494.57)	0.01	18125.50	255.44	287140.00
Simulation2: Surface Water (plus 25 %)	23301.31*** (494.69)	0.03	18125.50	255.31	287140.00
Simulation 3: Surface Water (plus 50 %)	23308.43*** (494.88)	0.06	18135.91	255.09	287140.00
Simulation 4: Surface Water (plus 100 %)	23322.69*** (495.28)	0.12	18149.44	254.67	287140.00

Note: Standard errors of the means in parentheses.

H_0: mean (simulation) = mean (baseline with observed allocation of groundwater)

H_A: mean (simulation) > mean (baseline with observed allocation of groundwater)

$^{*}\ p < 0.1$, $^{**}\ p < 0.05$, $^{***}\ p < 0.01$

The results for the allocative efficiency of groundwater are for farms in the sample that utilize groundwater.

[a] Percent change in the mean value of land productivity is calculated relative to the mean value of land productivity for Baseline (With Observed Allocation of Groundwater).

The implication of the analysis in this section is that increasing the share of total farm area with access to surface water improves the allocative efficiency of groundwater—the over utilization of groundwater decreases—which in turn leads to a modest increase in land productivity. Although increasing access to surface water is not sufficient in improving the utilization of groundwater, this policy matters in terms of improving equity in the distribution of surface water across farms and to reduce the shortfall in surface water irrigation.

3.7 Conclusion

In this Chapter, I used Stochastic Frontier Analysis to simulate the effect of access to surface water—a potentially important policy for Pakistan's irrigated agricultural sector—on the allocative efficiency of groundwater and on land productivity. I first estimated the allocative efficiency of groundwater in a profit maximization framework and included various locational and environmental covariates of allocative efficiency in the model. The covariates of the allocative efficiency of groundwater included: share of total farm area with access to surface water; shares of total farm area located at the head, middle and tail of a watercourse; shares of total farm area with good quality and medium quality groundwater; and shares of total farm area with three different soil types. Location on a watercourse is a proxy for both access to surface water and the reliability of surface water supply.

To avoid the problem of collinearity between access to surface water and location at the head, middle or tail of a watercourse, I estimated two models: a model that excluded location on a watercourse and a model that excluded access to surface water. The estimates of the allocative efficiency of groundwater showed that on average farms could increase income by about 6 percent by allocating groundwater efficiently. I found that the effect of access to surface water on the over utilization of groundwater is negative and statistically significant. Access to surface water allows farms to substitute more surface water for groundwater, which decreases the over utilization of groundwater.

I also found that the effects of being located at the head, middle and tail of a watercourse were negative and statistically significant in most specifications. This reconfirmed the hypothesis that access to surface water improves the allocation of groundwater. However, the effects of being located at the head, middle and tail of a watercourse were not statistically different from each other in all the specifications. The results suggested that the reliability of surface water supply (as measured by being located higher up on a watercourse) does not appear to explain the variation in the allocative efficiency of groundwater.

The estimation results suggested that increasing access to surface water might point to potential policies that could improve the allocative efficiency of groundwater and increase land productivity. I conducted four simulations to examine the economic impact of increasing access to surface water. The simulations showed that increasing the share of total area with access to surface water has a modest effect on land productivity—a maximum of 0.1 percent increase in income per hectare due to a 36 percent increase in the mean value of the share of total farm area with access to surface water. Though the policy simulation of increasing access to surface water did not demonstrate a significant improvement in the utilization of groundwater, the suggested policy, nonetheless, is important for improving equity in the distribution of surface water.

Conclusion

Pakistan’s agricultural sector relies heavily on water for irrigation, but declining water resources and a growing population will make Pakistan a water-stressed country in the near future. The current governance structure of water resources is inadequate to meet the growing demands of the agricultural sector. Pakistan urgently requires water policy reform to safeguard its water resources and to ensure sustainable economic growth. These goals can be achieved in part by directing policies towards efficient utilization and better management of water resources. However, institutional and farm-level constraints affect the utilization of water in the agricultural sector. Developing policies that ensure the sustainability of water resources needs to be evaluated in the context of the overall institutional environment of farms.

In this dissertation, I examined the utilization and management of groundwater in Pakistan taking into account existing farm-level constraints. I identified tenure, farm size, access to surface water and location on a watercourse as types of farm-level constraints that affect the utilization of groundwater, quantified the extent to which farms misallocate groundwater across these constraints and analyzed the effect of policy intervention on the allocation of groundwater and land productivity. I also evaluated the effects of separate groundwater management schemes, under different tenure arrangements, on the long run state of the aquifer and the annual income of farmers in the Indus Basin.

The literature is inconclusive, especially in the context of Pakistan, about the role of institutional constraints and the utilization and management of groundwater. I aimed at filling the gap in the literature by asking the following four questions:

1. How does the utilization of groundwater vary across different farm-level constraints?
2. What are the differences in the long run dynamics of groundwater extractions, groundwater quality, water table height and annual net benefits under common property management and optimal management?
3. What is the effect of existing tenure arrangements on different groundwater management schemes?
4. What are some of the policies that can improve the utilization of groundwater and to what extent?

The main findings in the dissertation are chapter specific and I have discussed them in detail within the respective chapters. Below I present synthesized answers to the research questions.

1. How does the utilization of groundwater vary across farm-level constraints?
    a. **Access to surface water:** Farms with access to both surface water and groundwater allocate groundwater more efficiently than farms that have access to only groundwater. Given the fixed allocations of surface water, and

its unreliability, farms with access to surface water might not meet their irrigation requirements with surface water alone. These farms might use groundwater to meet possible irrigation deficits. However, farms with only groundwater do not have any additional source of irrigation to meet their water requirements. Hence, these farms might over utilize groundwater.

b. **Tenancy:** On average, owner-cultivators and fixed-rent tenants over utilize groundwater while sharecroppers underutilize it. Fixed-rent tenants allocate groundwater more efficiently compared to owner-cultivators and sharecroppers. The province of Sindh has a higher share of sharecroppers and a higher share of farms with access to surface water compared to the province of Punjab. Since farms that have access to surface water tend to underutilize groundwater, the underutilization of groundwater by sharecroppers might be driven by the fact that a high share of sharecroppers has access to surface water compared to owner cultivators.

c. **Location on watercourse:** Farms located at the head of the watercourse and farms located at the middle of the watercourse tend to be more allocatively efficient than farms located at the tail of the watercourse. Since the allocation of surface water is uniform (fixed per unit of land) across all locations of a watercourse, farmers located at the tail of the watercourse are at a disadvantage given the unreliable supply of surface water. Farms at the tail of a watercourse might over utilize groundwater to compensate for the unreliable supply of surface water.

2. What are the differences in the long run dynamics of groundwater extractions, groundwater quality, water table height and annual net benefits under common property management and optimal management?
    a. Under common property management, groundwater extractions exceed the recharge of the aquifer and the water table height falls over time until it reaches a steady state. The groundwater salt concentrations increase over time due to the decrease in the volume of groundwater in the aquifer. The gradual fall in the water table height and deterioration of groundwater quality lead to a decrease in net benefits over time.
    b. Under optimal management, the high marginal user cost of groundwater causes groundwater extractions to be lower than the recharge of the aquifer. The water table height increases over time and reaches a steady state at the boundary condition. Groundwater quality improves initially as the water table height increases, but then deteriorates when the increase in salt mass exceeds the increase in the volume of groundwater in the aquifer. Net benefits increase initially but then fall as groundwater quality deteriorates.
    c. The benefits under optimal management exceed the benefits under common property management.

3. What is the effect of existing tenure arrangements on different groundwater management schemes?
    a. **Marshallian inefficiency:** In the tenure model (which includes owner cultivators and sharecroppers), 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 (includes only owner cultivators) under common property management. In the absence of Marshallian inefficiency the model would predict identical results for owner cultivators and sharecroppers.
    b. **Common property:** The 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 were small. The small share of total sharecroppers (10 percent) leads to unimportant differences between the results of the two models.
    c. **Optimal Management:** 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. The addition of the small share of sharecroppers has an insignificant effect on the baseline results.

4. What are some of the policies that can improve the utilization of groundwater and to what extent?
    a. **Increasing access to surface water:** Farms allocate groundwater more efficiently (over utilization decreases) as the share of total farm area with access to surface water increases. Increasing access to surface water is a potential policy that can improve the utilization of groundwater and increase land productivity.
    b. **Increasing the reliability of surface water supply:** location on the watercourse provides a measure of access to surface water and the reliability of the supply of surface water—location on a watercourse guarantees access to surface water while farms located higher up a watercourse have a more reliable supply of surface water. Farms allocate groundwater more efficiently (over utilization decreases) as the shares of total farm area located at the head, middle and tail of a watercourse increase. This result confirms the hypothesis that access to surface water improves the utilization of groundwater. However, the effects of being located at the head, middle and tail of a watercourse are not statistically different from each other. Therefore, increasing the reliability of surface water supply (as measured by being located higher up on a watercourse) does not appear to improve the utilization of groundwater.
    c. **Modest effect on land productivity:** Increasing the share of total area with access to surface water has a modest effect on land productivity—a

> maximum of 0.1 percent increase in income per hectare due to a 36 percent increase in the mean value of the share of total farm area with access to surface water. This result is driven by the fact that the unobservable fixed effect—included in the estimation—explains most of the allocative inefficiency of groundwater.

My research found evidence for certain drawbacks and limitations of policies that could improve the utilization of groundwater in Pakistan. The estimation results showed that increasing the reliability of surface water supply (as measured by being located higher up on a watercourse) does not appear to lead to a more efficient allocation of groundwater. Policy simulations (increasing access to reliable surface water) did not demonstrate a significant improvement in the utilization of groundwater. The suggested policies, nonetheless, are important in ensuring equity in the distribution of surface water. Farms located at the tail of the watercourse face an unreliable supply of surface water and depend on groundwater to meet irrigation shortfalls. Having access to a reliable supply of surface water would allow farms to limit their use of groundwater and conserve the resource. Further research is required to ascertain the impact of a more reliable and equitable distribution of surface water in improving rural livelihoods.

My research strongly suggests that policymakers in Pakistan should consider optimal management of groundwater over the status quo (common property management) to ensure the sustainability of the Indus Basin aquifer and to improve the livelihood of rural farmers in the basin. I described various quantity and price instruments that could be used to limit extractions to the optimal levels, but these policies 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. The analysis in the dissertation 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.

The efficacy of any proposed set of water policy reforms will depend on the prevailing institutional environment of water management. Placing potential reforms in this context should help determine the feasibility of these policies. The combination of empirical and policy results could help fill a knowledge gap about alternatives for the sustainable and productive use of irrigation water in Pakistan.

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Appendices

Appendix A:

In the tables below, PRHS-I(a) includes observations only from Punjab and Sindh, and PRHS-I(b) includes observations only from Khyber-Pakhtunkhwa (KP) and Balochistan.

Table A.1: Landholdings Statistics (Kanals) of the PRHS survey

	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
Mean Farm Size	85.6	76.5	103.4	76.8
Median Farm Size	32	32	24	32
Standard Deviation	303.3	129.0	491.0	136.8
Number of Households	1,383	919	464	814

Table A.2: Share of Landholding by Size Class (percent)

Size group (Kanals)	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
1-10	21	19	26	19
10-25	24	22	28	23
25-50	22	23	19	21
50-150	21	24	16	24
150-500	10	10	9	11
>500	2	2	2	1
Number of Households	1,383	919	464	814

Table A.3: Farm Size at Selected Percentiles (Kanals)

Percentile (percent)	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
10	6	7	4.75	7
25	12	16	10	16
50	32	32	24	32
75	76	80	60	80
90	168	192	160	200
95	304	310	280	320
100	8,000	1,376	8,000	1,880

Table A.4: Number of Plots Owned (percent)

Number of Plots	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
1	55	58	50	66
2	21	22	18	19
3	12	10	16	11
4	7	6	10	2
>5	5	4	6	1
Number of Households	1,307	871	436	811

Table A.5: Plot Size in the PRHS Samples (Kanals)

	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
Mean Plot Size	41.9	40.1	45.4	40.4
Median Plot Size	18	24	8	24
Standard Deviation	178.8	64.4	297.4	66.2
Number of Plots	3,519	2,357	1,162	1,917

Table A.6: Share of Plots by Tenure Classification (Owner-Cultivated and Leased-Out Plots)

	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
Kharif				
Owner-Cultivated	67.8	73.9	53.4	75.3
Leased-Out to Fixed-Rent Tenants	10.0	9.3	11.7	7.6
Leased-Out to Sharecroppers	22.2	16.8	34.9	17.2
Number of Plots	1,749	1,228	521	1,213
Rabi				
Owner-Cultivated	70.6	76.0	59.2	75.2
Leased-Out to Fixed-Rent Tenants	8.3	9.1	6.6	7.7
Leased-Out to Sharecroppers	21.1	14.9	34.2	17.1
Number of Plots	1,817	1,229	588	1,210

Table A.7: Share of Plots by Tenure Classification (Owner-Cultivated and Leased-In Plots)

	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
Kharif				
Owner-Cultivated	57.7	57.1	59.7	59.5
Leased-In by Fixed-Rent Tenants	9.3	8.5	11.8	10.8
Leased-In by Sharecroppers	33.1	34.4	28.5	29.7
Number of Plots	2,057	1,591	466	1,583
Rabi				
Owner-Cultivated	60	59.2	62.1	60.2
Leased-In by Fixed-Rent Tenants	9.5	9.4	9.6	10.8
Leased-In by Sharecroppers	30.5	31.4	28.2	29.0
Number of Plots	2,138	1,578	560	1,563

Table A.8: Change in Tenure Classification Over Seasons (Share of Owner-Cultivated and Leased-Out Plots)

PRHS-I

Tenure in Kharif (2000)	Tenure in Rabi 2001 Owner-Cultivated	Leased-Out to Fixed-Rent Tenants	Leased-Out to Sharecroppers
Owner-Cultivated	99.3	0.7	1.2
Leased-Out to Fixed-Rent Tenants	0.1	98	0.6
Leased-Out to Sharecroppers	0.6	1.4	98.3
Total	100	100	100

Based on 1,041 owner-cultivated, 147 fixed-rent, and 346 sharecropped plots

PRHS-I(a)

Tenure in Kharif (2000)	Tenure in Rabi 2001 Owner-Cultivated	Leased-Out to Fixed-Rent Tenants	Leased-Out to Sharecroppers
Owner-Cultivated	99.4	0.9	1.8
Leased-Out to Fixed-Rent Tenants	0.1	98.2	0.0
Leased-Out to Sharecroppers	0.5	0.9	98.2
Total	100	100	100

Based on 783 owner-cultivated, 109 fixed-rent, and 171 sharecropped plots

PRHS-I(b)

Tenure in Kharif (2000)	Tenure in Rabi 2001 Owner-Cultivated	Leased-Out to Fixed-Rent Tenants	Leased-Out to Sharecroppers
Owner-Cultivated	99.2	0.0	0.6
Leased-Out to Fixed-Rent Tenants	0.0	97.4	1.1
Leased-Out to Sharecroppers	0.8	2.6	98.3
Total	100	100	100

Based on 258 owner-cultivated, 38 fixed-rent, and 175 sharecropped plots

PRHS-II

Tenure in Kharif (2003)	Tenure in Rabi 2004 Owner-Cultivated	Leased-Out to Fixed-Rent Tenants	Leased-Out to Sharecroppers
Owner-Cultivated	100.0	2.2	1.5
Leased-Out to Fixed-Rent Tenants	0.0	97.9	0.0
Leased-Out to Sharecroppers	0.0	0.0	98.5
Total	100	100	100

Based on 908 owner-cultivated, 93 fixed-rent, and 204 sharecropped plots

Table A.9: Change in Tenure Classification over Season (Share of Leased-In Plots)

PRHS-I

	Tenure in Rabi 2001	
Tenure in Kharif (2000)	Leased-In by Fixed-Rent Tenants	Leased-In by Sharecroppers
Leased-In by Fixed-Rent Tenants	99.4	0.2
Leased-In by Sharecroppers	0.6	99.8
Total	100	100

Based on 180 fixed-rent and 569 sharecropped plots

PRHS-I(a)

	Tenure in Rabi 2001	
Tenure in Kharif (2000)	Leased-In by Fixed-Rent Tenants	Leased-In by Sharecroppers
Leased-In by Fixed-Rent Tenants	99.2	0.2
Leased-In by Sharecroppers	0.8	99.8
Total	100	100

Based on 130 fixed-rent and 445 sharecropped plots

PRHS-I(b)

	Tenure in Rabi 2001	
Tenure in Kharif (2000)	Leased-In by Fixed-Rent Tenants	Leased-In by Sharecroppers
Leased-In by Fixed-Rent Tenants	100.0	0.0
Leased-In by Sharecroppers	0.0	100.0
Total	100	100

Based on 50 fixed-rent and 124 sharecropped plots

PRHS-II

	Tenure in Rabi 2004	
Tenure in Kharif (2003)	Leased-In by Fixed-Rent Tenants	Leased-In by Sharecroppers
Leased-In by Fixed-Rent Tenants	100.0	0.0
Leased-In by Sharecroppers	0.0	100.0
Total	100	100

Based on 160 fixed-rent and 433 sharecropped plots

Table A.10: Share of Area Operated by Tenure (percent)

	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
Owner-Cultivated	58.8	57.8	64.1	66
Fixed-Rent	10.1	10.9	5.6	10
Sharecropped	31.1	31.2	30.3	24
Total	100	100	100	100

Table A.11: Plot Size by Tenure Status (Kanals)

PRHS-I	Mean	Median	Standard Deviation	Number of Plots
Owner-Cultivated	31.2	16.0	55.0	1434
Leased-Out to Fixed-Rent Tenants	25.9	12.0	44.0	182
Leased-Out to Sharecroppers	48.0	20.0	104.9	432
Leased-In by Fixed-Rent Tenants	36.1	16.0	56.3	215
Leased-In by Sharecroppers	31.1	24.0	32.1	765
PRHS-I(a)	Mean	Median	Standard Deviation	Number of Plots
Owner-Cultivated	35.0	18.0	59.9	1064
Leased-Out to Fixed-Rent Tenants	36.7	18.0	51.2	119
Leased-Out to Sharecropper	71.2	40	126.1	221
Leased-In by Fixed-Rent Tenants	45.1	24.1	62.7	156
Leased-In by Sharecroppers	34.0	24.0	26.4	598
PRHS-I(b)	Mean	Median	Standard Deviation	Number of Plots
Owner-Cultivated	20.1	8.0	35.1	370
Leased-Out to Fixed-Rent Tenants	5.5	4.0	5.2	63
Leased-Out to Sharecropper	23.7	8.0	68.8	211
Leased-In by Fixed-Rent Tenants	12.3	6.0	19.8	59
Leased-In by Sharecroppers	20.8	8.0	45.9	167
PRHS-II	Mean	Median	Standard Deviation	Number of Plots
Owner-Cultivated	34.3	20	47.6	915
Leased-Out to Fixed-Rent Tenants	49.5	16.9	83.2	94
Leased-Out to Sharecroppers	55.3	40.0	65.3	214
Leased-In by Fixed-Rent Tenants	43.9	24.0	115.8	180
Leased-In by Sharecroppers	31.0	24.0	25.6	490

Table A.12: Share of Plots that Receive Canal Irrigation (percent)

Canal Irrigation	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
Kharif Only	16.1	24.0	0.1	33.2
Rabi Only	1.1	1.6	0.0	0.1
Kharif and Rabi	33.2	41.7	15.7	39.4
No Canal Irrigation	49.7	32.8	84.2	27.3
Number of Plots	3,507	2,355	1,152	1,917

Table A.13: Share of Plots by Location on Watercourse (percent)

Location	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
Head	17.0	17.1	16.2	23.0
Middle	39.2	37.7	52.6	33.8
Tail	43.8	45.2	31.2	43.1
Number of Plots	1,742	1,569	173	1,393

Table A.14: Location on Watercourse of Plots that Receive Canal Irrigation (percent)

PRHS-I

	Location on Watercourse			
Canal Irrigation	Head	Middle	Tail	Total
Kharif Only	4.1	11.2	16.5	31.8
Rabi Only	0.2	0.6	1.3	2.1
Kharif and Rabi	12.5	26.4	25.7	64.6
No Canal Irrigation	0.1	1.0	0.4	1.6
Total	16.9	39.2	43.8	100

Based on 1,741 plots[23]

PRHS-I(a)

	Location on Watercourse			
Canal Irrigation	Head	Middle	Tail	Total
Kharif Only	4.5	12.4	18.3	35.3
Rabi Only	0.3	0.7	1.4	2.4
Kharif and Rabi	12.2	24.2	25.2	61.6
No Canal Irrigation	0.1	0.4	0.3	0.8
Total	17.03	37.8	45.2	100

Based on 1,568 plots

PRHS-I(b)

	Location on Watercourse			
Canal Irrigation	Head	Middle	Tail	Total
Kharif Only	0.0	0.0	0.0	0.0
Rabi Only	0.0	0.0	0.0	0.0
Kharif and Rabi	15.6	45.7	30.1	91.3
No Canal Irrigation	0.6	6.9	1.2	8.7
Total	16.2	52.6	31.2	100

Based on 173 plots

PRHS-II

	Location on Watercourse			
Canal Irrigation	Head	Middle	Tail	Total
Kharif Only	9.1	13.7	22.9	45.7
Rabi Only	0.1	0.1	0.0	0.1
Kharif and Rabi	13.9	20.0	20.2	54.2
No Canal Irrigation	0.0	0.0	0.0	0.0
Total	23.0	33.8	43.1	100

Based on 1,393 plots

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[23] One plot observation from Punjab and Sindh drops out because of missing data on canal irrigation.

Table A.15: Share of Plots with Groundwater Irrigation (percent)

Groundwater Irrigation	PRHS-I	PRHS-I(a)	PRHS-I(b)	PRHS-II
Good-Quality Groundwater	34.1	40.0	21.6	37.2
Medium-Quality Groundwater	8.9	11.0	4.7	8.7
Poor-Quality Groundwater	5.9	8.6	0.0	3.4
No Tubewell Irrigation	51.1	40.4	73.8	50.8
Number of Plots	3,328	2,256	1,072	1,917

Table A.16: Location on Watercourse of Plots that Use Groundwater Irrigation (percent)

PRHS-I

	Location on Watercourse			
Groundwater Irrigation	Head	Middle	Tail	Total
Good-Quality Groundwater	4.8	12.6	16.3	33.7
Medium-Quality Groundwater	1.4	5.1	6.2	12.7
Poor-Quality Groundwater	1.4	5.0	4.3	10.7
No Tubewell Irrigation	9.4	16.6	16.9	42.9
Total	17.1	39.2	43.7	100

Based on 1,733 plots

PRHS-I(a)

	Location on Watercourse			
Groundwater Irrigation	Head	Middle	Tail	Total
Good-Quality Groundwater	5.3	13.9	17.7	36.9
Medium-Quality Groundwater	1.60	5.4	6.9	13.9
Poor-Quality Groundwater	1.60	5.5	4.8	11.9
No Tubewell Irrigation	8.7	12.9	15.8	37.3
Total	17.2	37.7	45.1	100

Based on 1,560 plots

PRHS-I(b)

	Location on Watercourse			
Groundwater Irrigation	Head	Middle	Tail	Total
Good-Quality Groundwater	0.0	0.6	4.1	4.6
Medium-Quality Groundwater	0.0	2.31	0.0	2.3
Poor-Quality Groundwater	0.0	0.0	0.0	0.0
No Tubewell Irrigation	16.2	49.7	27.2	93.1
Total	16.2	52.6	31.2	100

Based on 173 plots

PRHS-II

	Location on Watercourse			
Groundwater Irrigation	Head	Middle	Tail	Total
Good-Quality Groundwater	6.6	11.8	14.3	32.7
Medium-Quality Groundwater	2.3	4.1	2.5	8.9
Poor-Quality Groundwater	0.7	1.1	2.2	4.0
No Tubewell Irrigation	13.5	16.9	24.1	54.5
Total	23.0	33.8	43.1	100

Based on 1,393 plots

Table A.17: Share of Plots that Use Canal and Groundwater Irrigation (percent)

PRHS-I

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	9.7	1.8	2.4	2.9	16.9
Rabi Only	0.3	0.2	0.3	0.4	1.1
Kharif and Rabi	7.5	4.9	3.0	19.6	34.9
No Canal Irrigation	16.6	2.1	0.2	28.2	47.2
Total	34.1	9.0	5.9	51.1	100

Based on 3,317 plots

PRHS-I(a)

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	14.3	2.7	3.5	4.3	24.8
Rabi Only	0.4	0.2	0.4	0.6	1.6
Kharif and Rabi	10.6	6.9	4.4	21.3	43.2
No Canal Irrigation	14.7	1.2	0.4	14.2	30.4
Total	40.0	11.0	8.7	40.4	100

Based on 2,255 plots

PRHS-I(b)

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	0.0	0.1	0.0	0.0	0.1
Rabi Only	0.0	0.0	0.0	0.0	0.0
Kharif and Rabi	0.8	0.5	0.0	15.8	17.0
No Canal Irrigation	20.7	4.1	0.0	58.0	82.9
Total	21.5	4.7	0.0	73.8	100

Based on 28 plots

PRHS-II

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	14.5	1.2	0.9	16.6	33.2
Rabi Only	0.1	0.1	0.0	0.0	0.1
Kharif and Rabi	9.2	5.3	2.0	23.0	39.4
No Canal Irrigation	13.5	2.2	0.5	11.2	27.3
Total	37.2	8.7	3.4	50.8	100

Based on 1,917 plots

Table A.18: Share of Plots Located at Head of Watercourse that Receive Canal and Groundwater Irrigation (percent)

PRHS-I

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	12.2	2.0	4.1	5.8	24.1
Rabi Only	0.0	0.0	0.3	1.0	1.4
Kharif and Rabi	15.3	6.4	4.1	48.1	73.9
No Canal Irrigation	0.3	0.0	0.0	0.3	0.7
Total	27.8	8.5	8.5	55.3	100

Based on 295 plots

PRHS-I(a)

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	13.5	2.3	4.5	6.4	26.6
Rabi Only	0.0	0.0	0.4	1.1	1.5
Kharif and Rabi	16.9	7.1	4.5	43.1	71.5
No Canal Irrigation	0.4	0.0	0.0	0.0	0.4
Total	30.7	9.4	9.4	50.6	100

Based on 267 plots

PRHS-I(b)

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	0.0	0.0	0.0	0.0	0.0
Rabi Only	0.0	0.0	0.0	0.0	0.0
Kharif and Rabi	0.0	0.0	0.0	96.4	96.4
No Canal Irrigation	0.0	0.0	0.0	3.6	3.6
Total	0.0	0.0	0.0	100.0	100

Based on 28 plots

PRHS-II

	Groundwater Irrigation				
Canal Irrigation	Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	15.0	0.9	1.9	21.5	39.3
Rabi Only	0.0	0.3	0.0	0.0	0.3
Kharif and Rabi	13.7	8.7	0.9	37.1	60.4
No Canal Irrigation	0.0	0.0	0.0	0.0	0.0
Total	28.7	10.0	2.8	58.6	100

Based on 321 plots

Table A.19: Share of Plots Located at Tail of Watercourse that Receive Canal and Groundwater Irrigation (percent)

PRHS-I

Canal Irrigation	Groundwater Irrigation Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	23.4	4.4	4.8	5.2	37.6
Rabi Only	0.7	0.4	1.1	0.8	2.9
Kharif and Rabi	12.7	9.4	4.1	32.5	58.6
No Canal Irrigation	0.7	0.0	0.0	0.3	0.9
Total	37.3	14.1	9.9	38.7	100

Based on 758 plots

PRHS-I(a)

Canal Irrigation	Groundwater Irrigation Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	25.1	4.7	5.1	5.5	40.5
Rabi Only	0.7	0.4	1.1	0.9	3.1
Kharif and Rabi	12.6	10.1	4.4	28.6	55.7
No Canal Irrigation	0.7	0.0	0.0	0.0	0.7
Total	39.2	15.2	10.7	34.9	100

Based on 704 plots

PRHS-I(b)

Canal Irrigation	Groundwater Irrigation Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	0.0	0.0	0.0	0.0	0.0
Rabi Only	0.0	0.0	0.0	0.0	0.0
Kharif and Rabi	13.0	0.0	0.0	83.3	96.3
No Canal Irrigation	0.0	0.0	0.0	3.7	3.7
Total	13.0	0.0	0.0	87.0	100

Based on 54 plots

PRHS-II

Canal Irrigation	Groundwater Irrigation Good-Quality Groundwater	Medium-Quality Groundwater	Poor-Quality Groundwater	No Tubewell Irrigation	Total
Kharif Only	22.3	1.2	0.7	29.0	53.1
Rabi Only	0.0	0.0	0.0	0.0	0.0
Kharif and Rabi	10.8	4.7	4.5	27.0	46.9
No Canal Irrigation	0.0	0.0	0.0	0.0	0.0
Total	33.1	5.8	5.2	55.9	100

Based on 601 plots

Appendix B:

Estimation results from the sample restricted to households observed only in kharif are given below.

Table B.1: Estimated Elasticities of the Variable and Quasi-Fixed Inputs (standard errors in parentheses) across Household Groups

	Overall
Hired Labor	0.02^{*} (0.01)
Fertilizer	0.78^{***} (0.02)
Groundwater	0.00 (0.00)
Own Male Labor	-0.05^{***} (0.01)
Own Female Labor	0.02 (0.05)
Capital	-0.01 (0.02)
Surface Water	-0.02 (0.02)

	Owner cultivated	**Fixed-rent**	**Sharecropped**
Hired Labor	0.02^{*} (0.01)	0.02^{*} (0.01)	0.00^{*} (0.00)
Fertilizer	0.81^{***} (0.02)	0.80^{***} (0.02)	0.77^{***} (0.02)
Groundwater	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Own Male Labor	-0.05^{***} (0.02)	-0.05^{***} (0.01)	-0.04^{***} (0.01)
Own Female Labor	0.02 (0.07)	0.02 (0.07)	0.03 (0.03)
Capital	-0.01 (0.02)	-0.01 (0.02)	-0.02 (0.02)
Surface Water	0.00 (0.02)	0.00 (0.02)	-0.08 (0.08)

	Small farm (<4 ha)	**Medium farm (4 to 10 ha)**	**Large farm (>10 ha)**
Hired Labor	0.00^{*}	0.02^{*}	0.02^{*}
	(0.00)	(0.01)	(0.01)
Fertilizer	0.78^{***}	0.77^{***}	0.79^{***}
	(0.02)	(0.02)	(0.02)
Groundwater	0.00	0.00	0.00
	(0.00)	(0.00)	(0.00)
Own Male Labor	-0.05^{***}	-0.04^{***}	-0.02
	(0.01)	(0.01)	(0.01)
Own Female Labor	0.03	0.00	0.01
	(0.04)	(0.07)	(0.07)
Capital	-0.01	-0.02	-0.01
	(0.02)	(0.02)	(0.02)
Surface Water	-0.03	-0.04	-0.00
	(0.03)	(0.03)	(0.02)

	With surface water	**Without surface water**
Hired Labor	0.02^{*}	0.00^{*}
	(0.01)	(0.00)
Fertilizer	0.78^{***}	0.81^{***}
	(0.02)	(0.02)
Groundwater	0.00	0.00
	(0.00)	(0.00)
Own Male Labor	-0.05^{***}	-0.05^{***}
	(0.01)	(0.02)
Own Female Labor	0.02	0.02
	(0.05)	(0.05)
Capital	-0.01	-0.03
	(0.02)	(0.02)
Surface Water	-0.01	-0.08
	(0.02)	(0.08)

Note: Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B.2: Estimates of Technical Efficiency (standard errors of the means in parentheses)

	Mean	Median	Min	Max
Overall	0.18 (0.00)	0.15	0.01	1.00
Owner-Cultivated	0.16 (0.01)	0.13	0.01	0.86
Sharecropped	0.21 (0.01)	0.18	0.03	1.00
Fixed-Rent	0.18 (0.03)	0.11	0.04	0.92
Small Farm (<4 ha)	0.18 (0.01)	0.14	0.01	1.00
Medium Farm (4 to 10 ha)	0.20 (0.01)	0.15	0.01	1.00
Large Farm (>10 ha)	0.19 (0.01)	0.16	0.03	0.39
With Surface Water	0.19 (0.00)	0.15	0.01	1.00
Without Surface Water	0.16 (0.01)	0.13	0.01	0.86
Head of Watercourse	0.20 (0.01)	0.18	0.01	0.77
Middle of Watercourse	0.19 (0.01)	0.15	0.01	1.00
Tail of Watercourse	0.17 (0.01)	0.14	0.01	0.92

Figure B.1: Cumulative Distribution Functions of Technical Efficiency by Tenancy Type

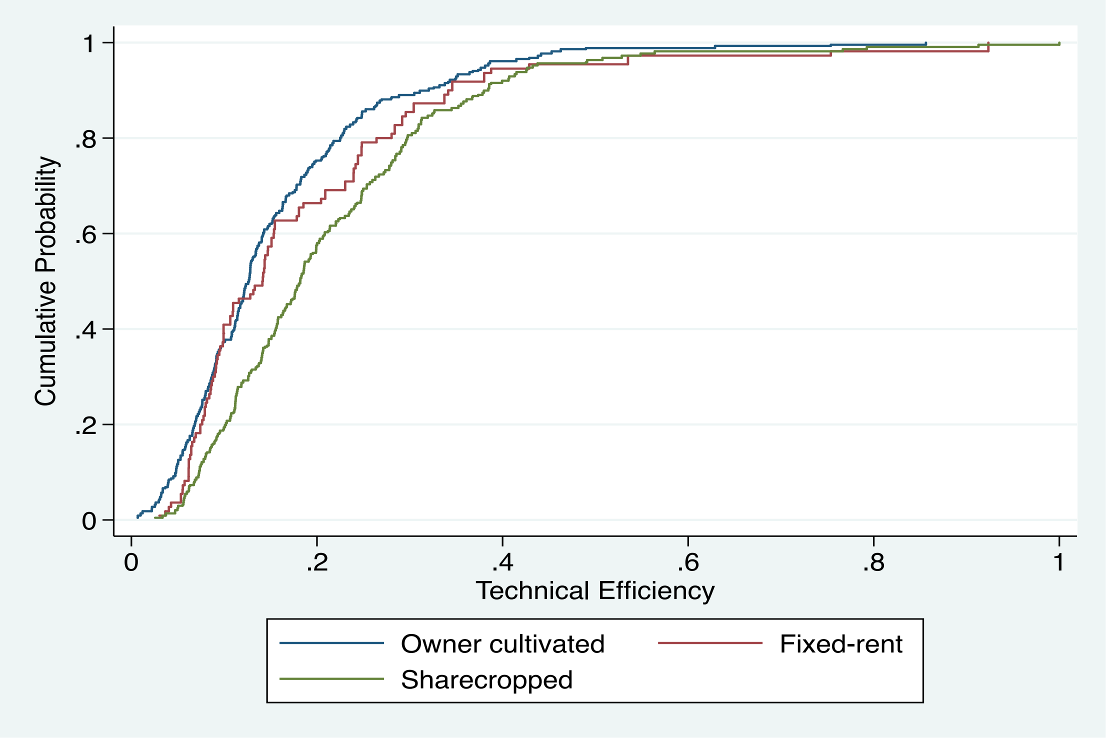


Figure B.2: Cumulative Distribution Functions of Technical Efficiency for Households with and without Surface Water

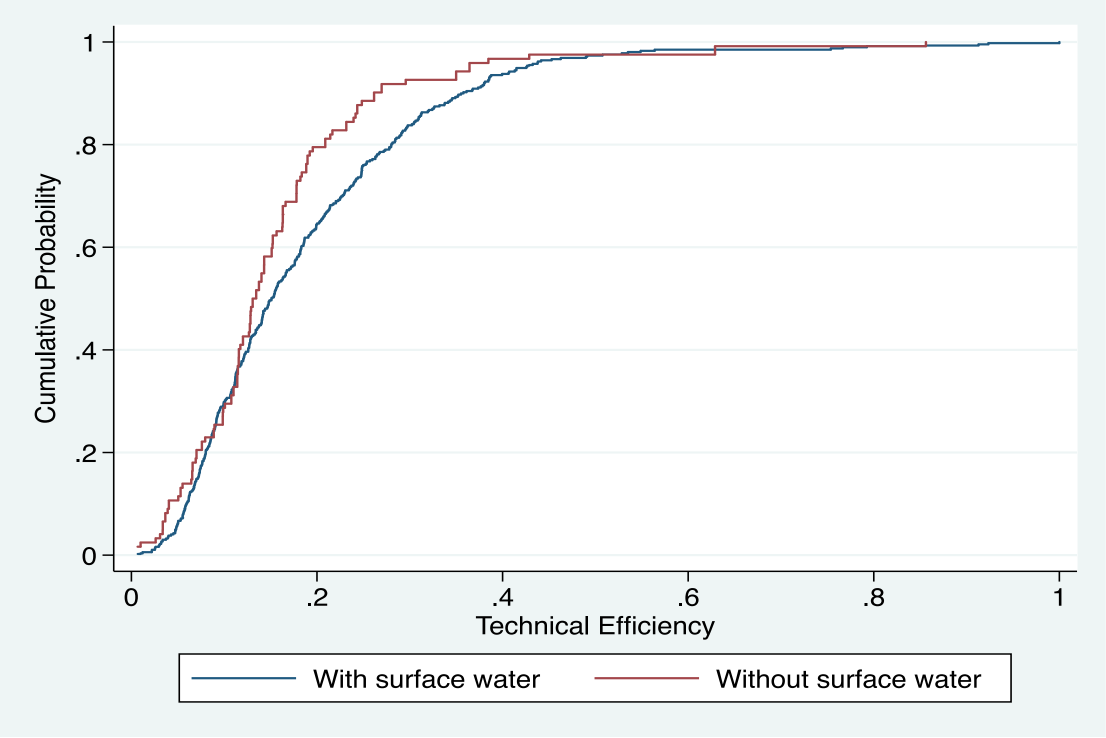


Table B.3: Estimates of Allocative Efficiency of Groundwater (standard errors of the means in parentheses)

	Mean	Median	Min	Max
Overall	6.46 (0.05)	6.45	3.87	10.07
Owner-Cultivated	6.59 (0.06)	6.57	4.02	10.07
Sharecropped	5.91 (0.15)	5.68	3.87	7.89
Fixed-Rent	6.48 (0.15)	6.27	5.21	9.10
Small Farm (<4 ha)	6.61 (0.05)	6.56	3.87	10.07
Medium Farm (4 to 10 ha)	6.08 (0.12)	6.14	4.02	10.07
Large Farm (>10 ha)	6.01 (0.13)	5.94	4.18	7.42
With Surface Water	6.36 (0.05)	6.37	3.87	8.63
Without Surface Water	6.69 (0.10)	6.62	4.39	10.07
Head of Watercourse	6.31 (0.13)	6.37	4.34	8.15
Middle of Watercourse	6.31 (0.09)	6.35	4.02	8.42
Tail of Watercourse	6.48 (0.09)	6.44	3.87	8.63

Figure B.3: Cumulative Distribution Functions of Allocative Efficiency of Groundwater Across Tenure Systems

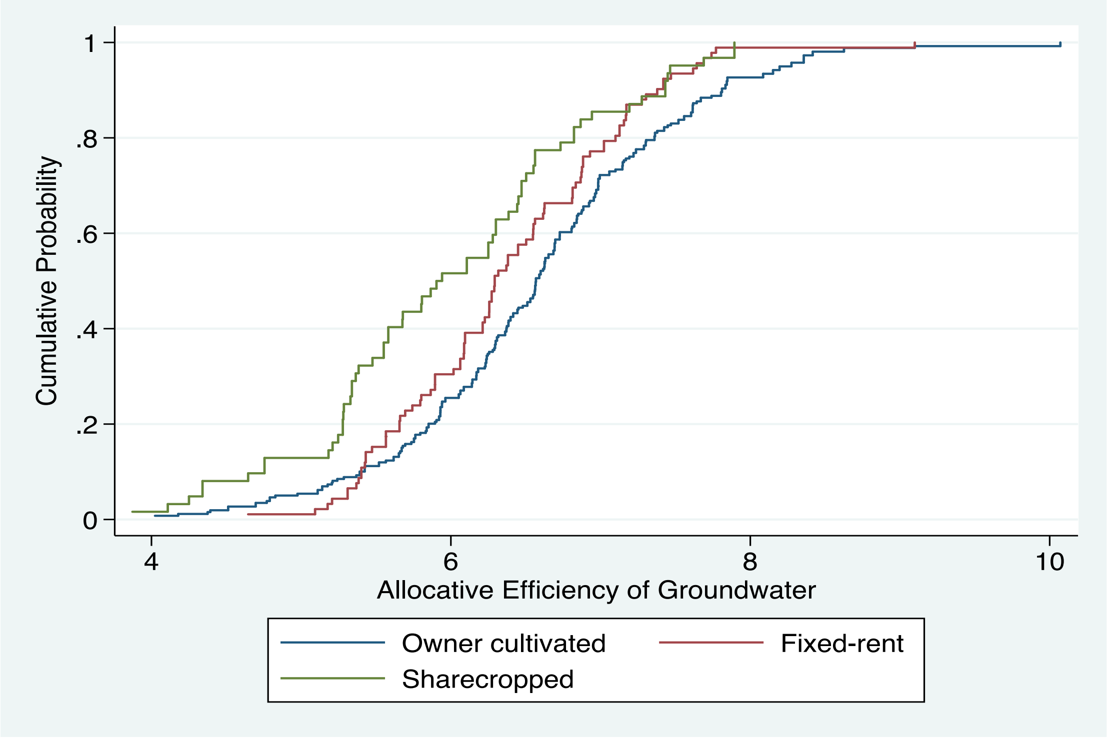
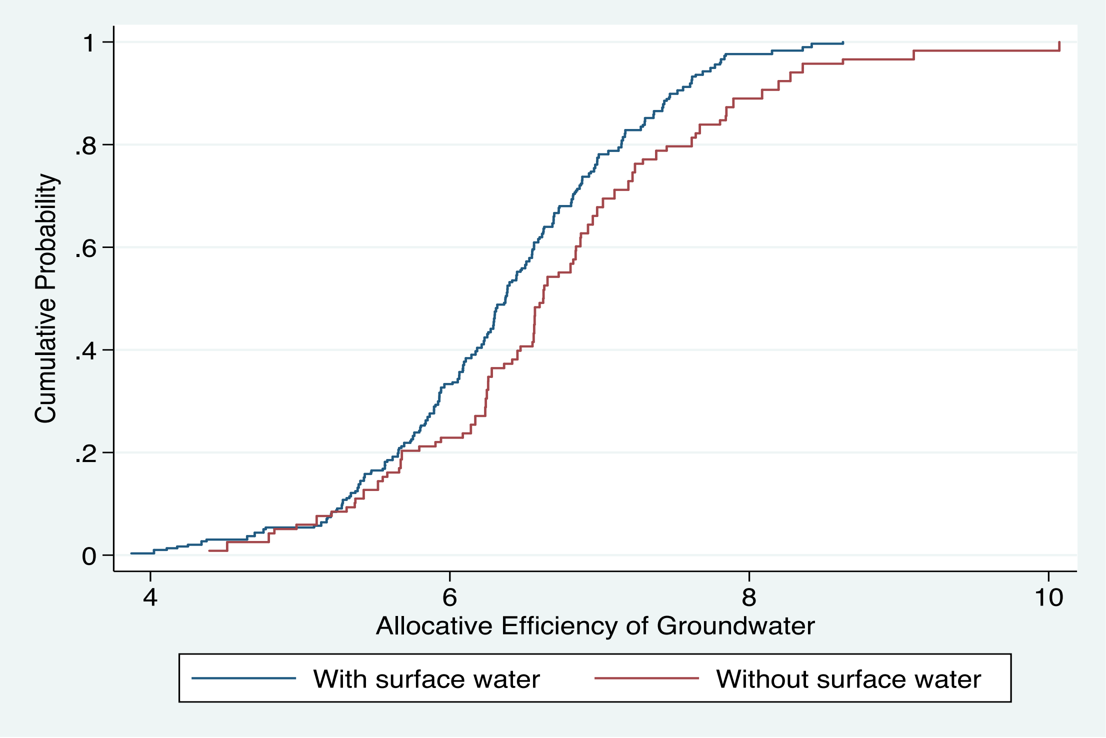


Figure B.4: Cumulative Distribution Functions of Allocative Efficiency of Groundwater Across Farms with and without Access to Surface Water.



Appendix C:

Estimation results from the sample restricted to households observed only in rabi are given below.

Table C.1: Estimated Elasticities of the Variable and Quasi-Fixed Inputs (standard errors in parentheses) across Household Groups

	Overall		
Hired Labor	0.00^{***} (0.00)		
Fertilizer	0.06^{***} (0.01)		
Groundwater	0.30^{***} (0.01)		
Own Male Labor	0.05^{***} (0.01)		
Own Female Labor	-0.03 (0.03)		
Capital	0.02 (0.02)		
Surface Water	0.04^{***} (0.01)		
	Owner-Cultivated	**Fixed-Rent**	**Sharecropped**
Hired Labor	0.00^{***} (0.00)	0.00^{***} (0.00)	0.00^{***} (0.00)
Fertilizer	0.06^{***} (0.01)	0.06^{***} (0.01)	0.06^{***} (0.01)
Groundwater	0.32^{***} (0.01)	0.33^{***} (0.01)	0.01^{***} (0.00)
Own Male Labor	0.05^{***} (0.01)	0.05^{***} (0.01)	0.05^{***} (0.01)
Own Female Labor	-0.04 (0.04)	-0.04 (0.04)	-0.02 (0.02)
Capital	0.01 (0.02)	0.01 (0.02)	0.04^{*} (0.02)
Surface Water	0.02^{*} (0.01)	0.02 (0.01)	0.08^{**} (0.04)

	Small Farm (<4 ha)	**Medium Farm (4 to 10 ha)**	**Large Farm (>10 ha)**
Hired Labor	0.00^{***}	0.23^{***}	0.28^{***}
	(0.00)	(0.01)	(0.01)
Fertilizer	0.06^{***}	0.06^{***}	0.06^{***}
	(0.01)	(0.01)	(0.01)
Groundwater	0.31^{***}	0.30^{***}	0.31^{***}
	(0.01)	(0.01)	(0.01)
Own Male Labor	0.05^{***}	0.04^{***}	0.02^{**}
	(0.01)	(0.01)	(0.01)
Own Female Labor	-0.02	-0.05	-0.04
	(0.02)	(0.04)	(0.04)
Capital	0.02	0.01	0.01
	(0.02)	(0.02)	(0.02)
Surface Water	0.04^{***}	0.03^{***}	0.02^{*}
	(0.01)	(0.01)	(0.01)
	With Surface Water	**Without Surface Water**	
Hired Labor	0.00^{***}	0.00^{***}	
	(0.00)	(0.00)	
Fertilizer	0.06^{***}	0.06^{***}	
	(0.01)	(0.01)	
Groundwater	0.19^{***}	0.33^{***}	
	(0.01)	(0.01)	
Own Male Labor	0.05^{***}	0.06^{***}	
	(0.01)	(0.01)	
Own Female Labor	-0.05	-0.03	
	(0.04)	(0.03)	
Capital	0.01	0.02	
	(0.02)	(0.02)	
Surface Water	0.02	0.08^{**}	
	(0.01)	(0.04)	

Note: Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table C.2: Estimates of Technical Efficiency (standard errors of the means in parentheses)

	Mean	Median	Min	Max
Overall	0.26 (0.01)	0.22	0.03	1.00
Owner-Cultivated	0.24 (0.01)	0.20	0.03	1.00
Sharecropped	0.30 (0.01)	0.27	0.03	0.89
Fixed-Rent	0.31 (0.03)	0.25	0.07	0.84
Small Farm (<4 ha)	0.25 (0.01)	0.21	0.03	1.00
Medium Farm (4 to 10 ha)	0.29 (0.01)	0.25	0.03	0.94
Large Farm (>10 ha)	0.34 (0.04)	0.33	0.07	0.84
With Surface Water	0.33 (0.01)	0.28	0.03	1.00
Without Surface Water	0.22 (0.01)	0.19	0.03	0.84
Head of Watercourse	0.28 (0.02)	0.25	0.03	0.76
Middle of Watercourse	0.30 (0.01)	0.24	0.04	0.89
Tail of Watercourse	0.27 (0.01)	0.23	0.03	1.00

Figure C.1: Cumulative Distribution Functions of Technical Efficiency by Tenancy Type

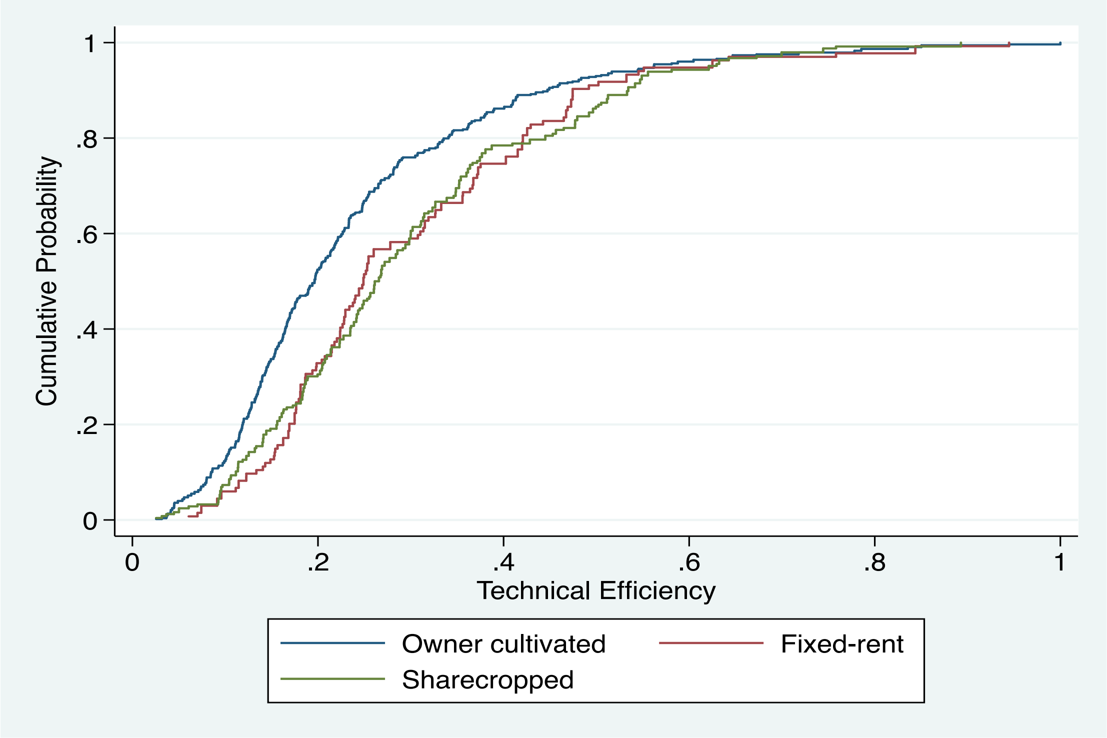


Figure C.2: Cumulative Distribution Functions of Technical Efficiency for Households with and without Surface Water

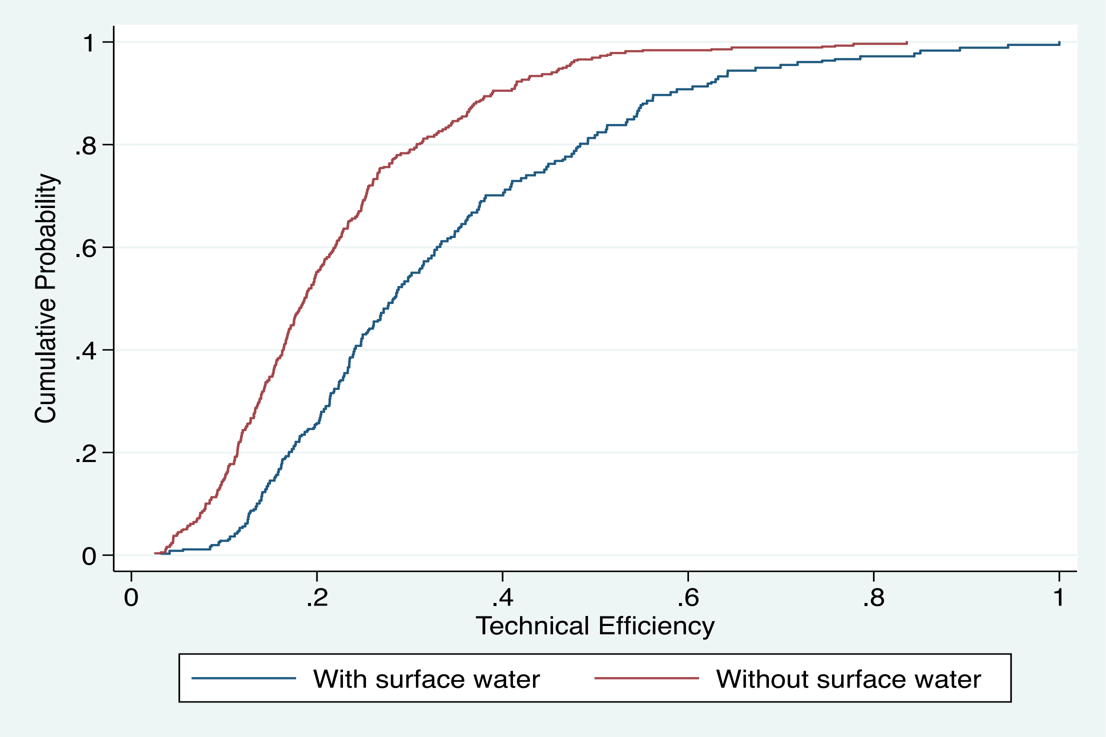


Table C.3: Estimates of Allocative Efficiency of Groundwater (standard errors of the means in parentheses)

	Mean	Median	Min	Max
Overall	-0.06 (0.03)	0.00	-1.90	1.96
Owner-Cultivated	0.03 (0.03)	0.11	-1.64	1.96
Sharecropped	-0.19 (0.08)	-0.28	-1.47	1.31
Fixed-Rent	-0.34 (0.11)	-0.27	-1.90	1.05
Small Farm (<4 ha)	-0.01 (0.03)	0.05	-1.64	1.96
Medium Farm (4 to 10 ha)	-0.25 (0.07)	-0.29	-1.64	1.53
Large Farm (>10 ha)	-0.35 (0.17)	-0.17	-1.90	0.46
With Surface Water	-0.39 (0.05)	-0.42	-1.90	1.18
Without Surface Water	0.10 (0.03)	0.14	-1.47	1.96
Head of Watercourse	-0.13 (0.09)	-0.09	-1.43	0.98
Middle of Watercourse	-0.18 (0.05)	-0.17	-1.90	1.00
Tail of Watercourse	-0.01 (0.05)	0.10	-1.90	1.18

Figure C.3: Cumulative Distribution Functions of Allocative Efficiency of Groundwater Across Tenure Systems.

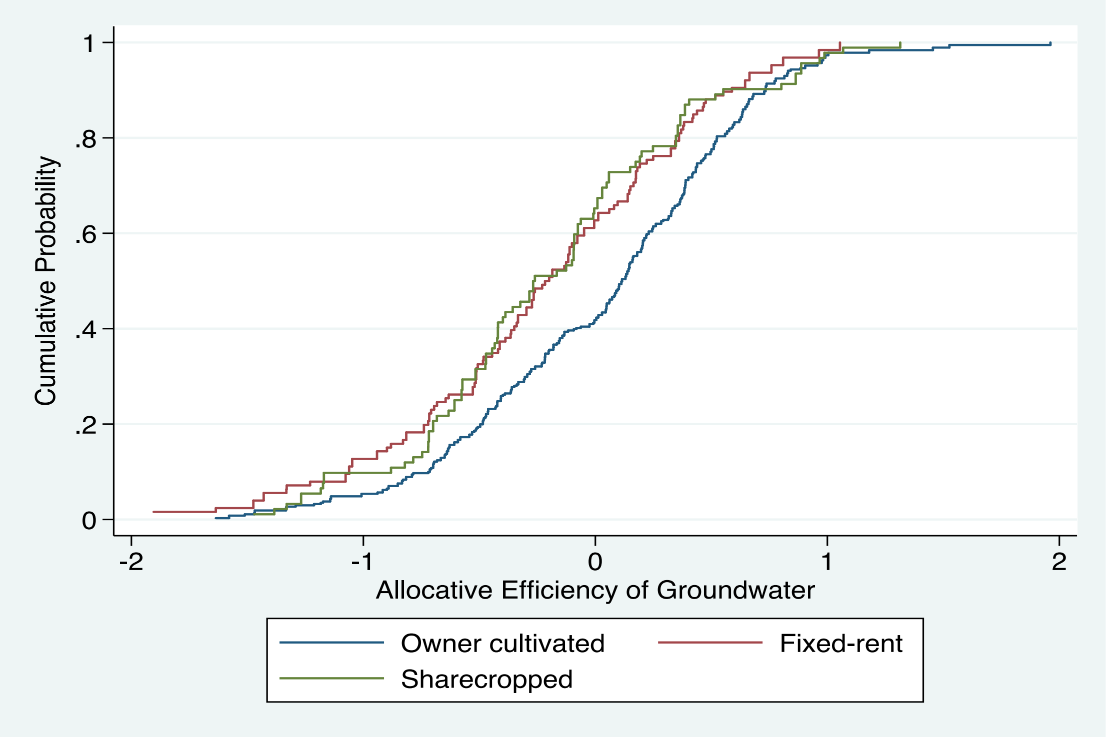


Figure C.4: Cumulative Distribution Functions of Allocative Efficiency of Groundwater Across Farms with and without Access to Surface Water