THREE ESSAYS ON THE ECONOMICS OF WATER MANAGEMENT IN AGRICULTURE

BY

MANI ROUHI RAD

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Agricultural and Applied Economics
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2017

Urbana, Illinois

Doctoral Committee:

Associate Professor Nicholas Brozović, Chair
Professor Amy Ando
Professor Alex Winter-Nelson
Professor Jeffrey Peterson

Abstract

This dissertation presents three essays on the economics of water management in agriculture. The overarching objective of the dissertation is to explore the effects of institutional setting and biophysical complexity on individual decisions around water use as an input. The focus of the dissertation is on agricultural systems that use groundwater as a source of irrigation. The first essay is an empirical study of the role of trading ratios and search frictions in a groundwater market with spatial externalities. Econometric results suggest that the use of trading ratios can indeed provide incentives for market participants to reallocate resources in a way that reduces spatial externalities. In the localized informal market I study, search frictions can be significant, with estimated loss of efficiency of up to 40%. In the second essay, I develop an analytical framework to explore policy implications of limitations imposed on groundwater flow rates by underlying aquifer characteristics. I find that limitations on the instantaneous supply of groundwater can affect irrigation decisions nonlinearly with a threshold effect. A profit-maximizing farmer with maximum available water flow rate below the threshold adjusts irrigation decisions on both the extensive (inter-seasonal) and intensive (intra-seasonal) margins. Above the threshold, optimally only intensive margin adjustment occurs. I further explore the role of heterogeneity in aquifer characteristics on the effectiveness of different aquifer management policies for Chase County, Nebraska, using a numerical model. I

find that under conditions of heterogenous instantaneous water availability, the burden of different policies may fall on different groups of water users in ways that have not been previously described. This result suggests that policy makers may need to consider the distributional effects of water management policies as well as their cost effectiveness. Finally, in the third essay, I analyze the effects of groundwater depletion on the loss of buffer value of an aquifer. The chapter develops a framework that captures nonlinearities in the effect of aquifer levels on the instantaneous supply of groundwater as well as the intra-seasonal nature of irrigation decisions. Applying the methodology to a portion of the High Plains Aquifer, I find that the costs of aquifer depletion may be greater than previously considered. Specifically, I show that loss of profit due to the inability to use groundwater to buffer against intra-seasonal variations of weather can be an order of magnitude higher than the loss of profit due to increased pumping costs. I also find that changes in aquifer levels have had quite different effects on buffer values across the area considered. The results suggest that while, on average, benefits to aquifer management in a given area may be small, there may be localized regions with large benefits.

To the people who provide public goods with no incentives.

Acknowledgments

First, I want to thank my advisor Nick Brozović for having significant influence on the way I think about problems of resource management. I also want to thank him for accepting to continue to be my advisor even after his move from the University of Illinois, as this was not a simple task and needed flexibility and extra effort. I also want to thank Amy Ando for always supporting me throughout the PhD studies. I always appreciated her frank assessments in the moments that I most needed them. I want to thank Alex Winter-Nelson for his wise suggestions during the later stages of my PhD studies. He always had a smart solution for complicated problems. I also thank Jeff Peterson for his suggestions and comments on my dissertation. These people are the ones that I always looked up to, and I believe I am a better person as a result of knowing them.

I want to thank my mom, my dad, and my sister for their continuous support for the past 30 years. They always provided support and love in difficult times and have always inspired me to learn and make progress. I hope one day I can pay back part of what they have done for me. I thank Liqing for her support and patience when I was writing the dissertation. Without her support, the task of wrapping up the dissertation would have been much more difficult.

Finally, I thank my friends who have helped me in my learning and growth during the PhD and in the later stages when writing the dissertation. Thank you Majid, Niu, Taro, Tim , Richael, Loki, Negin, Raul and Kashi.

This research was supported by USDA NIFA award numbers 2012-67003-23227 and 2015-68007-23133 and by cooperative agreement USDA ERS 58-6000-5-0027.

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CHAPTER 1

INTRODUCTION

Economists often prefer incentive-based policies such as taxes and tradeable permit markets in regulating activities that create a loss of social surplus. In practice, these policies are often implemented in settings that are different from the first-best settings in theoretical applications. For example, tradeable permit markets may be implemented in local and informal settings. On the other hand, in many coupled natural-human systems, underlying physical characteristics affect individual decisions nonlinearly. Uniform policies designed to reduce resource extraction, however, do not consider these nonlinearities. This dissertation intends to explore the role of limitations imposed by institutional settings and underlying physical characteristics on the effectiveness of natural resource management policies.

The analysis is applied to the management of agricultural systems with groundwater use. Agricultural production in many parts of the world depends on groundwater aquifers as the primary source of water supply. With declining aquifer levels, there is increasing demand in understanding the effect of changing aquifer levels on agricultural production and food security and the role of existing and proposed management policies in reducing aquifer depletion. However, the interaction between underlying aquifer characteristics and institutional settings, inter-seasonal and intra-seasonal farmer decisions and groundwater management policies is poorly understood within the existing literature. In this dissertation, I intend to bridge this gap by using theoretical, empirical and numerical analysis to answer specific questions regarding the management of groundwater aquifers in agricultural systems.

In Chapter 2, I study the effectiveness of a local and informal tradeable permit market in reallocating the resources in the presence of search frictions. Tradeable permit markets are recently emerging as a major policy tool for reducing environmental externalities such as water pollution and maintaining the sustainability of natural resources such as groundwater. While more sophisticated permit markets have been studied before, little empirical evidence exists on the performance of unsophisticated local markets in reallocating the resources. I consider a groundwater market that was designed to reduce depletion from a surface water body by limiting groundwater extraction from irrigated agriculture. The market was structured by setting a moratorium on new acres irrigated by groundwater and allowing transfer of irrigation rights based on a trading ratio system. While, in theory, trading ratio systems have been shown to provide incentives to individuals to move the resources in a direction to reduce non-uniform externalities, it is unclear whether this is the case in practice. In this chapter, I test whether, in practice, the market provides incentives to buyers and sellers to move groundwater extraction in the direction to reduce stream depletion. The results show that the market under study provides incentives that follow our expectations.

Furthermore, theoretical studies show that tradeable permit markets are a cost-effective way of reducing environmental externalities and reallocating resources. However, they have received criticism regarding their performance due to the presence of transaction costs such as search frictions. While anecdotal evidence exists in the presence of search frictions in these markets, there is no empirical evidence on this front. Using a theoretical framework, I provide testable hypothesis regarding the presence of search frictions in the market. I, then, test whether search frictions are significant in an informal groundwater market with no central market-clearing mechanism to provide insight into whether the market reallocates the resources cost-effectively. Finally, I estimate the upper bound of the efficiency loss due to search frictions to be 39% of the price of a permit. This chapter provides an empirical analysis using a unique geocoded dataset of trades in the Twin Platte Natural Resources District groundwater market in Nebraska that includes parcel specific characteristics. The dataset used in this study provides a significant advantage compared to previous studies on the presence of transaction costs.

In Chapter 3, I study policy implications of limitations imposed on groundwater flow rates by underlying aquifer characteristics and aquifer levels. Groundwater aquifers are complex physical bodies, and their underlying characteristics can affect the ecosystem services they provide. Specifically, physical aquifer characteristics impose limitations on the rate that a farmer can extract groundwater during the growing season. Agronomic studies suggest that groundwater availability during the growing season are critical for crop growth and production. Furthermore, they suggest that these limitations often directly affect farmers' irrigation decisions. However, existing economics literature and current policies do not take into account the effect of limited extraction rates on irrigation decisions of farmers and ignore the daily nature of irrigation decisions. As a result, these studies provide unrealistic conclusions regarding the effects of aquifer levels on irrigated agriculture. In this chapter, I develop an analytical framework to examine the effects of maximum available groundwater flow rate from an aquifer on a profit maximizing farmer's irrigation decisions about the number of irrigated acres and expected groundwater application per acre. The analytical results show that groundwater flow rate plays a fundamental role in farmers' irrigation decisions through its effect on potential crop yield. Specifically, I find that maximum flow rate affects irrigation decisions nonlinearly with a threshold effect. Profit-maximizing farmers with maximum flow rates below the switching point adjust their number of irrigated acres to be able to meet crop water demand during the critical stages of the growing season on the irrigated acres. This adjustment of irrigated acres can result in significant loss of profit.

Underlying aquifer characteristics are often heterogeneous across parcels, even at small scales such as counties. As a result, instantaneous groundwater supply significantly varies across parcels, resulting in differential irrigation decisions among individual farmers. This spatial heterogeneity and its effect on irrigation decisions can have significant implication for the choice of aquifer management policies. I build on the analytical results and develop a numerical model to study the cost-effectiveness and distributional effects of different policies for reducing aquifer depletion within irrigated agriculture in Chase County, Nebraska. The results show that the cost-effective policy may not be the best policy when local aquifer depletion is of concern. This surprising result occurs because the cost-effective policy, the pumping tax, provides larger incentives for farmers with greater well capacities, while an acreage tax can provide incentives to farmers with lower well capacities to reduce their extraction.

Finally, in Chapter 4, I estimate the loss of buffer value of an aquifer as a result of depletion of the resource. Groundwater aquifers provide a reliable source of water supply for irrigated agriculture that enables farmers to buffer against weather variations. However, as a result of aquifer depletion, the maximum flow rate that one can extract groundwater from an aquifer decreases nonlinearly. This nonlinearity combined with nonlinear effects of maximum flow rate on irrigation decisions and profit can result in significant loss of buffer value due to aquifer depletion. In this chapter, using the theoretical model developed in chapter 3, I introduce a framework to study the changes in buffer value of an aquifer due to aquifer depletion taking into account the interaction between aquifer characteristics and intra-seasonal nature of irrigation decisions. I, then, apply the methodology to a part of the High Plains aquifer which includes five counties in Nebraska and Kansas to estimate the loss of buffer value between 1980 and 2009. This chapter has several major findings. First, I find that costs of aquifer depletion can be greater than previously considered. Specifically, I show that loss of profit due to inability to buffer against intra-seasonal variations of weather can be an order of magnitude higher than the loss of profit due to increasing pumping costs. Second, I find that changes in aquifer levels have had significantly different effects on the buffer value of aquifer across the region even within local areas. Many existing studies that focus on the value of aquifer management find relatively small benefits to management. The findings in this chapter suggest that while the average effects on the entire management area may be small, there can be significant benefits to aquifer management within parts of a management area. Finally, the findings show that changes in buffer value do not entirely correlate with changes in aquifer levels. This is because other factors affect the changes in buffer value of aquifers such as initial aquifer levels and heterogeneity in aquifer characteristics. This finding suggests that merely focusing on changes in aquifer levels does not provide the full picture and may result in providing misleading policy recommendations. The approach presented in this chapter captures realistic biophysical relationships and their effect on irrigation decisions and provides an outcome that is relevant in introducing policies.

While all the chapters of this dissertation have focused on the management of groundwater resources in agricultural production, the questions and results in this dissertation have more general implications. In many of the existing and emerging problems within the context of environmental and resource economics, we can observe similar physical and institutional limitations that affect individuals' decisions. Tradeable permit markets are being used widely to manage externalities and control the extraction of natural resources while, in cases such as fisheries, the size of the stock could have a nonlinear effect on optimal vessel size, effort and the number of quotas held. Finally, the interaction of underlying physical and institutional characteristics and individuals response can affect the effectiveness of different policies in many similar cases.

CHAPTER 2

IMPLICATIONS OF SEARCH FRICTIONS FOR TRADEABLE PERMIT MARKETS

2.1 Introduction

With increased stress on groundwater aquifers due to increasing demand and changing climatic conditions, and with our improved understanding of surface water and groundwater interactions, the popularity of groundwater markets is growing among policymakers (Aladjem and Sunding, 2015). However, little empirical evidence exists on their performance in reallocating the resource. In this chapter, I study the performance of a groundwater market that was designed to reduce depletion from a surface water body by limiting groundwater pumping from irrigated agriculture and allowing trades among participants. I address two questions regarding the performance of the market. First, does the market provide incentives to move the resources in a direction to reduce stream depletion in practice? Second, are search frictions significant in this market? I estimate an upper bound for search costs in the market to gain insight into whether resource reallocation is cost-effective.

Several studies exist on the design and cost-effectiveness of spatially explicit environmental management policies. Most of these studies focus on the design of pollution permit systems (Montgomery, 1972; Hung and Shaw, 2005). Kuwayama and Brozović (2013) analyzed cost saving from adopting a spatially explicit permit system for groundwater pumping to reduce stream depletion. They show that at the optimal allocation, the price of a permit (for pumping one unit of groundwater) will be relative to a well's marginal impact on the stream. Since the distance to the stream is a significant factor in the marginal impact, they show that wells closer to the river will have a higher price for a permit than wells at larger distances. A market with trading ratios for permit prices can create incentives for wells farther away from stream to purchase permits. While intuitive, no empirical evidence for this claim exists in the literature. Trading ratios are most common in controlling water pollution and air pollution. However, experiences within these markets have been mostly unsuccessful. Hoag and Hughes-Popp (1997) mention trading ratios as one of the reasons that resulted in low participation in the Tar-Pamlico River Basin water quality trading among point and nonpoint pollution sources.

Furthermore, in theory, we know that tradeable permit markets can be a cost-effective way of reducing environmental externalities (Montgomery, 1972). They provide significant advantages over other incentive-based policies, including flexibility to the right holders (Colby, 1990). However, due to the presence of transaction costs, whether permit markets achieve their objectives cost-effectively in practice is an empirical question. Ideally, we would want to answer whether tradeable permit markets are cost-effective in a "second-best" world when we can compare the cost-effectiveness of a tradeable permit market with other alternatives as counterfactuals (Anderson and Parker, 2013). While an appropriate counterfactual world is often not easy to identify, we can study the performance of markets regarding reallocation of resources (Ghimire and Griffin, 2014; Hadjigeorgalis, 2009) and the presence of transaction costs.

Limited evidence exists on the performance of tradeable permit markets compared to other policies in practice. The only study that the author is aware of is Fowlie et al. (2012). They show that the REgional CLean Air Incentives Market (RECLAIM) in California has reduced emissions by 20% compared to a command-and-control policy. However, the performance of tradeable permit markets in practice has often come under question. One of the main critiques, especially at the local level, has been low participation rates (Hoag and Hughes-Popp, 1997; Young, 1986; McCann, 1996). The existence of transaction costs is suggested to be a primary reason for low participation rates in permit markets (Hahn and Hester, 1989b; Stavins, 1995). Transaction costs in this context are two types: administrative costs, such as establishing the market, monitoring and enforcement (Krutilla and Krause, 2011) that are usually borne by the administration; and costs of market transactions, such as making decisions, search, and bargaining. Market participants carry these costs.

Market structure can also affect the costs borne by individuals. This study provides insight into the presence of search costs in a local, informal groundwater market with no central market clearing mechanisms. Most previous studies have considered the cases of more sophisticated and active markets, such as RECLAIM (Gangadharan, 2000; Fowlie et al., 2012) and lead phase-down (Kerr and Maré, 1998). Kerr and Maré (1998) studied the efficiency of the lead phase-down market in the presence of transaction costs. Although this market is considered one of the most successful examples of tradeable permit markets to date, 70% of transactions took place between refineries of the same companies. The preponderance of internal trades is consistent with the existence of large transaction costs in the market. Kerr and Maré (1998) find that smaller companies, smaller refineries and "refineries that do not have other refineries to trade with within their company" are less likely to trade. They study transaction costs as a function of firm characteristics and do not consider quantity traded. They conclude that while tradeable permit markets can be the cost-effective policy, markets with "small, non-integrated and unsophisticated" participants could be less cost-effective.

Gangadharan (2000) studied firms' participation decisions in the RECLAIM while considering transaction cost covariates. They mention that most facilities that trade multiple times tend to trade with the same trading partner and this could be due to high search costs. They divide the facilities into two groups: those that traded multiple times (low search cost) and those that traded with different partners (high search costs). They show that search and information costs can be significant and reduce the probability of trade by more than 30%. However, their data do not include firm-level characteristics. Furthermore, like Kerr and Maré (1998), they assume fixed transaction costs.

Most water quantity and quality markets are informal and local. Carey et al. (2002) suggest that "formal markets are the exception rather than the rule" and develop a framework to study an informal water market with no central market clearing mechanism and no publicly available prices for trades. They define a network within which transaction costs are zero and compare trades within and outside the network. They assume fixed transaction costs which are homogenous among farmers. Their model provides hypotheses regarding the frequency and size of the trades. Using the data from the Westlands water market in California, they provide some evidence that while the number of trades is higher for internal trades, the average size of trades is larger in external trades.

Regnacq et al. (2016) study the impacts of fixed and variable transaction costs on trading behavior using the gravity model. They explain that variable costs of transferring water between buyers and sellers (which includes conveyance costs and transaction costs) depend on distance. They use district level data of bilateral trades between 237 districts in California and focus on short term leases from 1995 to 2007. They show that for a longer physical distance between the districts, both the probability of trade between them (extensive margin of trade) and the size of trade between the districts (intensive margin of trade) decrease.

In this paper, I provide testable hypotheses regarding trading behavior and search effort for profit-maximizing farmers in a market with search frictions. I test the hypotheses for the case of the Twin Platte Natural Resources District (TPNRD) groundwater market in Nebraska. In this district, a well construction moratorium was set in place in 2004 to reduce stream depletion from the Platte River, but transfers of groundwater rights based on depletion from the Platte river were allowed. While most previous studies have used aggregate data to study the performance of water markets (Colby et al., 1993; Howitt, 1994; Hansen et al., 2007), this study analyzes a parcel-level, geocoded dataset of trades. Tietenberg (2005) mentions three types of studies in assessing the performance of tradeable permit markets: studies that focus on Pareto optimality, studies that focus on cost-effectiveness, and studies on market effectiveness. This study falls into the third category. Unlike the first two, it does not compare the current regulation with a baseline scenario (e.g. command-and-control) or global performance of the market and instead focuses on the performance of the market given existing conditions.

The results provide evidence regarding the performance of the market in reallocating groundwater extraction away from the river that follows intended market structure. Furthermore, the results suggest that search frictions are significant in the market reducing its cost-effectiveness. The upper bound on the size of transaction costs is estimated to be around 40% of the price of groundwater.

2.2 Model

This section provides a theoretical framework of a profit maximizing farmer searching for a trading partner in a market with search frictions. The model considered here is applied to a market for groundwater pumping rights. However, it can be generalized to other natural or common pool resources.

Tradeable permit markets for natural resources are designed by setting a cap on the aggregate extractable quantity of the resource and allowing trades among individuals. Initially, the permits could be auctioned off or grandfathered. The latter is usually the case for water rights because the rights were established long before the markets were set in place. Due to profitability of using the resource as an input, there is a demand for extracting the resource. This demand often depends on time varying factors such as prices and weather conditions where changes in time varying factors can result in differential changes in demand among heterogenous individuals. The binding constraint on available permits and profitability of using the resource creates a market where those who have higher marginal values for the resource can buy the rights from those who have lower marginal values.

Tradeable permit markets are often local and informal such that prices of permits (or rights) are not publicly known and buyers and sellers need to engage in a costly search process to find a trading partner. Search frictions can have important implications for performance of markets in allocating resources between supply and demand sides (Mortensen, 2011).

The framework used in this section is based on the model considered by Mortensen (2011). Similar models have been used in understanding the performance of labor markets, housing markets, and marriage markets (Rogerson et al., 2005), but they have not been used in understanding the performance of tradeable permit markets. In this model, buyers and sellers engage in a costly process of finding each other while maximizing their expected income.

The decision of a buyer or a seller to trade is composed of two parts. First, the individual maximizes their profit function to get the quantity they want to trade, Q. Then, they look for a trading partner maximizing their expected payoff, $\mathbb{E}\sum_{t=0}^{\infty} V$. Assuming a two step decision means that the quantity traded is predetermined in the search process. In the next section, I provide some argument that this assumption holds for the case of the market under study.

Thus, I take Q as given and exogenous to the search decision.

Buyers and sellers meet based on a matching function, $m(u, v)$ which is a function of the number of potential buyers, v, and potential sellers, u. This function is increasing in both arguments, i.e. an increase in the number of participants on either side will increase the flow of contracts. Further, it is assumed that the matching function is homogenous of degree 1 in both arguments so that the meeting rate for buyers and sellers is only a function of $(\frac{v}{u})$ which is called the market tightness. The meeting rate for a seller is $\varepsilon_s = \frac{m(u,v)}{u}$ and for a buyer it is $\varepsilon_b = \frac{m(u,v)}{v}$. These meeting rates are exogenous to buyers and sellers[1].

For a seller, the problem is whether to sell their permits at a price drawn from a known distribution, received from the potential buyer they met in time t, or wait another period to find another buyer. Assuming an infinite life for the farmer[2], if they decide to sell their water rights at price ω, payoff will be:

$$rW_s(\omega) \quad = \quad r\omega Q + \pi^0 Q \tag{2.1}$$

where r is the interest rate and it is assumed to be fixed over time, $W_s(\omega)$ is the seller's payoff from selling their rights, Q is the quantity sold, and π^0 is per unit profit of producing without the input. Equation 2.1 shows that the payoff from selling permits is equal to the total amount that the seller receives plus the infinite stream of income from producing without the input. On the other hand, the seller can keep their permits and wait to find another buyer. In that case, their payoff is:

$$rU_s \quad = \quad \pi^1 Q + \alpha_s \varepsilon_s \int_0^{\bar{\omega}} Max\{0, W_s(\omega) - U_s\} \, \mathrm{d}F(\omega) - g_s(\alpha_s) \tag{2.2}$$

where U_s is the payoff from not selling rights in the current period, π^1 is the profit of producing with the input, $\bar{\omega}$ is the upper limit of permit prices in the market, and $F(.)$ is the CDF of prices. The seller can increase the probability of finding a buyer, α_s, by increasing their effort, $g_s(\alpha_s)$, where $g_s^{'} > 0$ and $g_s^{''} > 0$. Equation 2.2 shows that the payoff of not selling the

[1] I relax this assumption in the empirical section.

[2] Alternatively, we can assume a death rate with Poisson distribution, but this does not qualitatively change the analysis.

rights is equal to profit from producing with input plus expected gain from finding a buyer in the future and making a trade. Equations 2.1 and 2.2 form the Bellman equations for the seller.

Because $W_s(\omega)$ is strictly increasing in ω there exists a reservation price, R_s, where $W_s(R_s) = U_s$. It is the minimum price the seller is willing to accept to sell their permits. If they receive a price higher than the reservation price, they will sell their permits, while if the price is lower than R_s the individual will wait for another buyer. Solving equations 2.1 and 2.2 for R_s, we get:

$$R_s = \frac{\Delta\pi_s}{r} + \frac{\alpha_s \varepsilon_s}{r} \int_{R_s}^{\bar{\omega}} (1 - F(\omega)) \, \mathrm{d}\omega - \frac{g_s(\alpha_s)}{Q} \tag{2.3}$$

R_s depends on the profit differential, $\Delta\pi = \pi^1 - \pi^0$, and the price per unit of permit, ω, less the per unit costs of search. Appendix 1 explains how parcel-specific factors affect profit differentials in the context of groundwater-fed irrigation. Taking the first order conditions to get the optimal effort we have:

$$g_s'(\alpha_s) = \frac{\varepsilon_s Q}{r} \int_{R}^{\bar{\omega}} (1 - F(\omega)) \, \mathrm{d}\omega. \tag{2.4}$$

Equations 2.3 and 2.4 explain the behavior of a seller in the market. It can be seen that the profit differential positively affects reservation price. Participation of the buyers' side affects the trading activity of the sellers in two opposite ways: first, for a given reservation price, an increase in participation of buyers will increase the chance of meeting a potential buyer and thus increase a seller's probability of trading their water rights. Second, an increase in the participation of buyers increases the reservation price for a seller making them less likely to sell their permits. Labor market literature suggests that the former effect is stronger and thus an increase in the participation of buyers increases trading activity of sellers. However, prices in the market will increase as a result of higher reservation prices (Mortensen, 2011)[3]. Notice that search effort only depends on volume of trade and participation in the market, and not on profits. Thus, in the case that quantity is exogenous to search effort, we do not expect parcel level characteristics to

[3] In the labor market literature the Beveridge curve shows the relation between vacancies and employment.

affect search effort. The Bellman equations for a buyer are similar:

$$rW_b(\omega) = -r\omega Q + \pi^1 Q \tag{2.5}$$

$$rU_b = \pi^0 Q + \alpha_b \varepsilon_b \int_0^{\bar{\omega}} Max\{0, W_b(\omega) - U_b\} \, \mathrm{d}F(\omega) - g_b(\alpha_b) \tag{2.6}$$

The first equation shows the stream of income if the individual were to buy Q units of permits and the second equation shows the payoff from not buying rights and continuing to produce without the input[4]. The reservation price for the buyer is defined as the maximum price they are willing to pay so that they are indifferent between using the input for production and not using it. Solving equations 2.5 and 2.6 for R_b and α_b we get:

$$R_b = \frac{\Delta\pi_b}{r} + \frac{\alpha_b \varepsilon_b}{r} \int_0^{R_b} F(\omega) \, \mathrm{d}\omega - \frac{g_b(\alpha)}{Q} \tag{2.7}$$

$$g_b'(\alpha_b) = \frac{\varepsilon_b Q}{r} \int_0^{R_b} F(\omega) \, \mathrm{d}\omega. \tag{2.8}$$

From equations 2.3 and 2.7 we can see that as a seller's profit differential increases, their reservation price goes up and the seller is less likely to sell their permits. If a buyer's profit differential increases, their reservation price also increases and the buyer is more likely to buy permits. Since $g(.)$ is convex in α, equations 2.4 and 2.8 suggest that as the size of a trade increases, search effort of a buyer or a seller increases.

The situation is complicated if there is a spatial externality that requires application of a trading ratio or transfer coefficient to transfers. When a trading ratio is applied, we can assume that price per unit of permit paid by a buyer is $(\frac{\omega}{\beta})$, where β is the ratio of the transfer coefficient of the seller to that of the buyer. Thus, β directly affects the price paid by a buyer. In the system the way it is defined, it is more expensive to buy a permit from a seller with a lower trading ratio than to buy it from a seller with a higher trading ratio. This suggests that there will be a higher demand from sellers with higher trading ratios. Similarly, we can argue that sellers with a higher

[4] An advantage of this model over a neoclassical model is allowing heterogeneity of buyers' and sellers' opportunity costs of trade. Instead of assuming that every agent can simply be a buyer or seller and obtaining demand and supply curves, here their opportunity cost depends on the type of activity they are engaged in.

trading ratio receive higher prices per unit of permit and are more likely to sell their permits.

2.3 Study Area

2.3.1 Twin Platte Natural Resources District

In 1969, 24 Natural Resources Districts (NRDs) were established based on L.B. #1357 in accordance with natural river basins in Nebraska[5] (Figure 2.1). NRDs were originally designed for water development projects, but their responsibilities toward other land and water management, development and protection programs in the districts have increased over time. The Twin Platte Natural Resources District (TPNRD) is located within the Platte River Basin and along the Platte River. It is responsible for management of land and water in Arthur and Keith Counties and two-thirds of Lincoln and McPherson Counties in western Nebraska (Figure 2.2). Agriculture is the primary user of groundwater in the TPNRD and the major crop produced in the district is corn. Average acres under corn production is about six times larger than soybeans and almost six times that of wheat, the second and third crops produced in Nebraska. Based on reports from University of Nebraska extension, irrigated corn yields are on average more than three times that of dryland corn in Nebraska and the gap is widening. The increasing difference between dryland and irrigated yields has created a high demand for irrigation within the state. An increase in corn prices within the past decade has further increased the demand for irrigation.

Due to interconnections between groundwater and surface water, Nebraska's Department of Natural Resources (DNR) is required to evaluate surface water supplies in each NRD every year and determine whether basins are "fully appropriated" or "overappropriated". If the use of water resources causes or is believed to contribute to future limitations in water supply, the NRD will be considered overappropriated. In 2004, DNR designated TPNRD as overappropriated which meant that an immediate stay on constructing new wells and increasing irrigated acres was put in place and that TPNRD was

[5] A merger in 1989 reduced that number to 23 Natural Resources Districts.

required to develop a management plan to reduce consumption to sustainable levels (Bleed and Babbitt, 2015). As a result of the management plan, TPNRD only allows transfer of irrigated acres from one location to another location such that the transfer does not lead to further increase in stream depletion.

2.3.2 Rules of the Market

TPNRD is responsible for management of water resources within the district and has designed rules and regulations for water transfers to comply with the limitations set by DNR. TPNRD only allows trades within the district and rights cannot be sold to or bought from groundwater users outside the district. Furthermore, before any farmer can start irrigation, TPNRD has to approve the trade including the number of acres that can be irrigated. TPNRD is also responsible for monitoring and enforcement of the trades.

Groundwater rights in the district are defined based on the area of land under irrigation and not the amount of water extracted. Thus, there is no allocation or limit on the amount of groundwater that can be applied on irrigated acres. While land rights and groundwater rights are defined separately, farmers can only trade groundwater for acres under irrigation such that when a farmer sells their groundwater right for an acre, that acre should not be irrigated anymore. Furthermore, only permanent trades are allowed to take place, and no leases or temporary transfers are allowed. To reduce monitoring costs, TPNRD only approves trades that include an entire parcel or certain portions of a plot that can easily be verified and monitored during the growing season.

Since the primary purpose of the moratorium on the number of acres irrigated was to reduce depletion from the Platte River, TPNRD defined a transfer coefficient that translates pumping one unit of groundwater by a farmer at a particular location within the district into expected depletion from the river. This transfer coefficient is called the Stream Depletion Factor (SDF). A unique SDF is assigned to each section in the district. It is calculated mainly based on hydraulic conductivity, saturated thickness, storage coefficient, distance to the surface water feature and distance to the aquifer boundary.

To ensure that withdrawals from the river do not increase as a result of transfers and perhaps even decrease over time, transferring irrigated acres in the district is only allowed based on the stream depletion factors of the old parcels and new parcels. Furthermore, transfers are "unidirectional" and are adjusted in an asymmetric fashion. If the SDF of the new acres is less than that of the old acres, the number of acres transferred can remain the same. If the SDF of new acres is higher than the SDF of old acres, the numbers of acres transferred decreases proportionally to the increase in SDF. This adjustment ensures that stream depletion will either decrease or stay the same after trading. Based on the argument presented in the previous section, when the market is unidirectional, sellers with higher trading ratios are still more likely to sell. However, in this case, buyers with lower trading ratios do not pay a lower price per permit and are not more likely to buy.

2.3.3 Sources of Transaction Costs

There are two types of transaction costs in tradeable permit markets: costs of implementation and costs of transactions. The first group is concerned with designing the institutions, implementing the market, monitoring and enforcement. These costs are usually borne by the governing body of the market[6]. In the case of the TPNRD groundwater market monitoring costs are shared between the district and traders. Although TPNRD is responsible for monitoring, imposing limitations on acres traded passes some of the costs to traders. On the other hand, transaction costs for participants are those of gaining information about the market, making decisions, search costs and bargaining costs.

The TPNRD groundwater market is an informal water market. There are different definitions of informal water markets available within the literature depending on the focus of the authors on various aspects of these markets. In a more general definition, Carey et al. (2002) define an informal market as an immature market where prices are not publicly known. In a study of Australian water markets, Bjornlund (2004) defines an informal market as one where the transfer of rights is temporary rather than permanent. Finally, Easter et al. (1999) define informality by the enforceability of trades

[6] Sometimes traders bear some of the costs, e.g. in some air pollution markets, participants were responsible for monitoring and reporting the amount of pollution.

compared to formal markets. In this study, I use a definition closer to Carey et al. (2002). Specifically, by an informal market I mean the situation where trades are "coffee shop trades" and the search process usually consists of buyers or sellers looking for each other by asking around if others are willing to trade. There were no formal brokers present in the market during the period of this study. Buyers and sellers had to search for potential traders, which can be very costly. Search costs in the market, like most thin environmental markets, are expected to be significant. Evidence for high search costs is the dominance of internal trades and that most of the external trades take place between neighboring buyers and sellers where more than half of the trades took place within a distance of 5 miles (figure 2.3). Furthermore, in a well-functioning market, we expect higher value trades to occur earlier during the period when the market is active; in the sample studied here this is not the case. Higher value trades take place during later years of market activity perhaps due to the lack of information about the market during the early stages of market activity and high information costs in the market.

Since gains from trade increase when there is more heterogeneity between a buyer and a seller, and since there are spatial correlations in physical characteristics of parcels, a short distance between traders could suggest that traders forgo benefits of trading with more heterogeneous partners to avoid high costs of finding a better trade.

2.4 Data

This study uses data on 92 trades that occurred between 2005 and 2013. The data is a confidential dataset from TPNRD and contains the number of acres traded in each transaction and information about buyers and sellers including their geographic location. One of the advantages of the data over previous studies is that parcel specific characteristics are available for irrigated acres. However, we do not have access to the location of dryland acres that do not trade. This is because dry acres do not deplete the Platte River and are not of interest to TPNRD. A disadvantage of the dataset, though, is that it does not contain prices of trades.

Field level data include soil type, pump rate and depth to water. The data for well characteristics are collected from the Nebraska Department of

Natural Resources well database which is publicly available. The data on soil qualities are collected from the U.S General Soil Map (STATSGO) of the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA). Futures prices of corn and diesel are retrieved from the Quandl futures database. Precipitation data for North Platte Airport station has been retrieved from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). Tables 2.1 and 2.2 show the summary statistics for parcel level, district level, and market-level characteristics for sellers and buyers. While the number of trades is small, we can see significant variation across parcels. Furthermore, major changes in the price of corn and weather conditions have resulted in differences in district level characteristics. Figure 2.3 shows the distribution of distances between new and old acres. As can be seen from this figure, most of the trades have taken place within a 5 miles radius which is consistent with high search costs in the market.

2.5 Econometric Strategy

The empirical part of the study comes in two parts. The first part studies whether the market tends to move groundwater extraction away from the river to that stream depletion decreases, while the second part studies whether volume traded affects the physical distance between buyers and sellers.

2.5.1 Effects of Stream Depletion Factor on Probability of Trade

In this section, I examine the effects of stream depletion factor on the probability that a seller will sell their groundwater rights, or a buyer will buy groundwater rights. As discussed in previous sections, the Twin Platte Natural Resources District adjusts trades in a unidirectional manner based on the stream depletion factor. We expect this market structure to provide incentives for sellers with higher SDF to be more likely to sell and buyers with lower SDF to be more likely to buy. I test these hypotheses using logit models for sellers and buyers separately, controlling for market-level time-varying factors and parcel level characteristics.

Two different regressions for sellers and two regressions for buyers are estimated. In the first regression, I directly control for time-varying factors such as output price, the input price, and precipitation at the district level. Due to data availability, I make some simplifying assumptions. Since the major crop in the district is corn, it is assumed that corn is the only crop produced. Further, it is assumed that all the irrigating parcels use diesel as fuel for pumping groundwater. The unit of observation is a parcel of land and the farmer owning an irrigated parcel makes the decision to sell their irrigation rights for the parcel, and a farmer owning a dryland parcel decides whether to buy water rights to irrigate their parcel. The data for the sellers' regression comes from the subsample of irrigated parcels while the data for the buyers' regression comes from the subsample of dryland acres. The logit regression model for sellers and buyers is as follows:

$$Prob(sell = 1|X) = \frac{exp(\beta_0 + \beta_1 X + \beta_2 SDF)}{1 + exp(\beta_0 + \beta_1 X + \beta_2 SDF)} \tag{2.9}$$

$$Prob(buy = 1|X) = \frac{exp(\beta_0 + \beta_1 X + \beta_2 SDF)}{1 + exp(\beta_0 + \beta_1 X + \beta_2 SDF)} \tag{2.10}$$

where X is a vector of district level characteristics such as the price of diesel, price of corn, precipitation, and parcel specific characteristics such as soil quality, pump rate and well depth. SDF is stream depletion factor, and β_2 is the coefficient of interest. We expect that a higher output price, a lower input price, and a lower precipitation will increase market participation. Furthermore, we expect that farmers with higher pump rates will be less likely to sell and more likely to buy. Pump rate is a major factor in determining irrigation decisions and is discussed in more detail in chapter 3. We expect that farmers with deeper water levels will be more likely to sell and less likely to buy since depth to water determines cost of pumping. Finally, we expect medium soil qualities to be more likely to buy and low and high soil qualities to be more likely to sell their water rights. Mathematical derivation of this claim is provided in the Appendix. The intuition is that low quality soils have low capacity to hold water, while high quality soils can capture most of the precipitation. As a result, the difference between irrigated and non-irrigated profits is highest among some medium range of soil qualities where irrigation can affect profits significantly.

The second logit model I estimate uses year dummies instead of time-varying variables. These dummies control for all the factors that change from year to year within the district. There may be other district-level time-varying factors that affect the decision to trade which the first model does not include. These variables may bias the effect of SDF on the decision to trade. If they are correlated with SDF, the second model will be able to capture these effects and produce unbiased estimates.

2.5.2 Effect of Volume of Trade and Market Participation on Distance Between Buyers and Sellers

In this section, I estimate the effects of quantity traded on search effort of participants. Here, the distance between a buyer and a seller is used as a proxy for the search effort. In a market with no search frictions, we expect to see no relationship between quantity traded and physical distance between buyers and sellers. Here, I test the null hypothesis that amount traded does not affect the physical distance between buyers and sellers. The following OLS regression estimates the effect of volume of trade on the distance between buyers and sellers controlling for market, climatic, and spatial factors:

$$distance_i = \alpha_0 + \tau_1 X_i + \tau_2 Q_i + \epsilon_i \tag{2.11}$$

where X is a vector of time-varying variables and spatial parcel characteristics. The first group includes the price of diesel, price of corn and precipitation. These factors can affect market conditions (for example, the number of participants). The second group includes stream depletion factor and portion of irrigated acres in a 2-mile radius. These factors can affect the location of a parcel. For example, if a potential seller is located in a region with high soil quality and water quality such that their neighbors are also irrigating and they have a higher density of irrigated acres, they might need to find buyers at a longer distance. A similar explanation holds for buyers. Finally, I include the difference between sellers and buyers SDF to control for the fact that distance may be merely driven by the difference in SDF rather than quantity traded. Q is quantity traded and we are interested in τ_2.

One important assumption in estimating the effect of quantity traded on distance is that quantity traded does not change over distance (and time). The reason to believe this assumption holds in the case of TPNRD is that the rights are defined based on acres and TPNRD does not allow the transfer of quantities of acres that are difficult to monitor. Thus the decision to buy or sell the rights should be made before looking for a trading partner. Furthermore, these decisions are usually in forms that are also agriculturally feasible, for example removing an end gun, drying half of a center pivot circle or drying the entire parcel. There is also anecdotal evidence suggesting that farmers decide the quantity they want to buy or sell and do not change that quantity over time.

A concern that might arise in the OLS model is selection bias. This bias may be of concern if those who decide to trade their water rights are different from those who do not trade based on some unobservable characteristics. In that case, the estimate will be biased and will not be representative of the effect on the entire population. To correct this selection bias, a Heckman two-step regression model is estimated where covariates of the first stage are the same as the logit model. We run both OLS and Heckman two-step models with time-varying covariates and with year dummies.

2.6 Results

2.6.1 Effects of Stream Depletion Factor on Probability of Trade

The results of logit regressions for trading activity of sellers and buyers are shown in Table 2.3. Marginal effects at mean values are shown in Table 2.4. The probability that a seller will sell their groundwater rights when all variables are kept at their mean is estimated to be 0.52%, while the probability that a buyer will buy new water rights keeping everything at their mean is 0.22%. Estimated probabilities look small mainly because the number of individuals who traded their groundwater rights is much smaller than those who did not participate in the market.

From Table 2.3 we can see that the effect of stream depletion factor on sellers is significant, while the effect on buyers is not significant. These results hold for both regressions, and the coefficients are the same suggesting that prices of corn and diesel, and district level precipitation can control for most time-varying variables. While the marginal size of the effect is small due to a significant number of non-participants in the market, the direction and significance of both coefficients can be informative for the performance of the TPNRD groundwater market. The positive sign on the stream depletion factor for the sellers suggests that controlling for parcel level and market level variables, sellers with higher stream depletion factors are more likely to sell their groundwater rights. Stream depletion factor does not affect the probability of trade for buyers. One reason for this finding might be that while sellers with higher SDF have higher incentive to sell their permits because they are more competitive in the market, buyers with lower SDF do not necessarily have more incentives to buy the permits. As long as the SDF of a buyer is lower than that of a seller, there is no advantage of having lower SDF. This is consistent with the unidirectional nature of trades in the market. Furthermore, buyers with lower SDF may have lower present value for their investment. This is because if they decide to resell their water rights in the future, they may be at a disadvantage because of their low SDF. The other explanation is the presence of transaction costs of finding trading partners. When search frictions are present in the market, buyers end up trading with their neighbors. As we can see from Figure 2.4 most irrigated acres are initially located in areas with high SDF. The presence of search costs within the TPNRD is further discussed in the next subsection.

From Table 2.3 we can also see that most of the coefficients follow our expectations. Corn prices have a positive and significant effect on participation and probability of trade for both buyers and seller. Furthermore, an increase in precipitation decreases the probability of trade for both sides, and in drier years we are more likely to see trades taking place. Pump rate also has a significant effect which suggests that it is an important variable in the decision to trade groundwater rights. Sellers with higher pump rate are less likely to sell, and buyers with lower pump rate are less likely to buy. The coefficients on soil quality for sellers follows our expectation suggesting that sellers with medium soil quality are less likely to sell. These results also suggest that the relationship between soil quality and the probability of participating in trade is non-monotonic for sellers. However, it does not follow our expectation for the buyers showing buyers with both medium and high-quality soil are more likely to buy groundwater rights than those with low-quality soils. The reason might be that maximum profit differential for buyers takes place at a soil quality that is different from our definition of medium soil quality which is silty soil.

2.6.2 Effect of Trade Quantity on Physical Distance

Effects of acres trades on physical distance for sellers and buyers are shown in tables 2.5 and 2.6. In each table, column 1 shows the estimates from OLS regression using prices and precipitation, column two shows OLS estimates with time dummies, column 3 shows the Heckman selection model with prices and precipitation and column 4 shows estimates for the Heckman model with time dummies. Columns 3 and 4 only show the results of the second stage of Heckman's model.

The results show that quantity traded has a positive and significant effect on distances between buyers and sellers in most regressions. For sellers, the effect is significant in all regressions and is between 0.058 and 0.089 miles per acre of groundwater sold. For buyers, the effect is only significant when we include time dummies and the effect is between 0.067 and 0.071 miles per unit of groundwater rights bought. Interpreting distance as a proxy for search costs, one possible explanation is that those with larger quantities traded expect higher gains from trade and invest more in searching for a trading partner. These results have two major implications. First, in a market with no search frictions we expect quantities traded not to have any effect on physical distance between buyers and sellers and distance should be randomly distributed. However the positive coefficient on quantities traded suggests that this is not the case and search frictions are, in fact, significant in this market. While previous studies have either looked at fixed transaction costs of trades, or studied legal costs of trade ignoring search and bargaining costs, I show that search costs are important and need to be considered. Furthermore, while previous studies have mainly focused on the effect of transaction costs on the probability of participation (extensive margin of trade), these results focus on the effects of transaction costs for the trades that have already taken place (intensive margin of trade). Second, as explained previously, in the market considered here, the quantities desired to be traded are determined prior to the search process. These results suggest that the presence of high search costs results in buyers or sellers who want to trade smaller quantities to do so within a close physical distance. This trading behavior, however, results in loss of efficiency because of spatial autocorrelation in physical parcel and aquifer characteristics. Due to spatial autocorrelation, parcels that are closer to each other have less profit differential than parcels that are at a longer distance.

Furthermore, the results show that both buyers and sellers with higher SDFs search significantly shorter distances for trading partners. These results confirm the findings in previous sections that one reason those with higher stream depletion factors are more likely to trade is the presence of search frictions. These results also suggest that presence of search costs can affect those with lower SDF more significantly.

Comparing the results of OLS with the Heckman 2-step model, the results show that selection is not significant for sellers and coefficients are very close. However, the standard errors and significance levels suggest that the inverse Mills ratio is correlated with some of the variables[7]. For buyers, the selection into trade is significant. However, the effect of selection bias is very small and the coefficients are close to OLS.

While I provided some evidence regarding the exogeneity of quantities to the search process due to farmers' decision processes and market structure, here, I provide further evidence that quantity traded is predetermined in the search process. If we assume that quantity is not predetermined in the search process, we expect buyers or sellers to change their initially determined quantities as a result of the search process. Since the market is thin and no single price exists within the market, we expect prices to be determined separately within trades. While we do not have access to prices of transactions and prices are determined within a negotiation process, we can expect gains from irrigation to affect the maximum willingness to pay and minimum willingness to accept such that buyers with higher profit differential (from irrigation) offer higher prices per "acre" of groundwater rights while sellers with lower profit differential accept lower prices. Thus, we might expect quantity sold to be affected by the buyer's profit differential and quantity bought to be affected by the seller's profit differential. Tables 2.7 to 2.10 suggest that

[7]This multicollinearity is one of the limitations of the Heckman model when the first and second steps have elements in common, e.g. Bockstael et al. (1990).

this is not the case. In Table 2.8, the first two columns provide the results of regressing quantity purchased on buyers' characteristics while the last two columns show the result of regressing quantity sold on the difference between parcel-level characteristics of the buyer and the seller. Similarly, the first two columns of table 2.10 show the results of regressing quantity bought on sellers' characteristics while the last two columns show the results of regressing quantity bought on the difference between the buyer and the seller's characteristics. These two tables suggest that parcel-level characteristics of trading partners do not have a significant effect on quantity traded. Tables 2.7 and 2.9 show the results of regressing physical distance of trades on quantity traded controlling for parcel-level characteristics of the trading partner and the difference between parcel-level characteristics of the trader and the trading partner. These tables provide further evidence that profit differential of the trading partner does not significantly affect the coefficient of quantity traded. Taken together, these regressions suggest that quantity is not endogenous to the search process.

2.6.3 Loss of Efficiency

In order to understand how significant search frictions are, we need to study loss of efficiency that resulted from these transaction costs. To provide an estimate of the size of transaction costs, I compare gains from trade for the trades that had taken place to gains from trade if the individuals had traded with a potential trading partner that maximized gains from trade. Gains from trade were estimated as the difference between profit differential of a buyer and profit differential of a seller where profit differential is the difference between irrigated and dryland profits. Since I do not have data on parcel level profits, I use the Water Optimizer program (Martin et al., 2007) to estimate irrigated and dryland profits for each parcel. Water Optimizer estimates average profit based on crop choice, irrigation type, fuel type, parcel level characteristics and water availability. I estimated profit for each parcel by taking into account the prices in a given year, soil type, irrigation type (center pivot or gravity) and water characteristics[8]. Further, I assumed all

[8]I estimated depth to water table from the closest monitoring USGS well. However, as cost of pumping does not significantly affect profit for the variations observed, I assumed an average depth to water table of 100 feet for all parcels.

parcels grow corn and use diesel as fuel.

Using the outputs from Water Optimizer, loss of gains from trade due to transaction costs were estimated. Since a buyer and a seller in a trade each could have their own "gain-maximizing" partner, I sum improvements on gains from trade over all buyers and all sellers[9]. In aggregate, loss of efficiency due to transaction costs in the Twin Platte Natural Resources District is estimated to be $616,000 per year in nominal terms. Loss of efficiency for sellers is estimated to be $229,000 per year, while it is estimated to be $387,000 per year for buyers. On average, total efficiency loss is equal to $59 per acre traded, or $64 per acre in 2016 dollars.

National Agricultural Statistical Service shows an average cash rent of $209 per acre for irrigated lands and $64 per acre for dryland in Lincoln county in 2016. The difference between irrigated and dryland land rental values shows the annual value of groundwater for each acre, which is estimated to be $145. Based on these values, efficiency loss due to search frictions is estimated to be 39%.

Several points are worth noting here. First, The estimates reported may be considered as an upper bound since all the potential trades may not take place in the counterfactual world. Furthermore, this estimate may include other transaction costs such as limitations imposed by the TPNRD on transferring irrigated acres. Finally, Colby (1990) finds the average size of policy-induced transaction costs including application and legal costs of purchasing water rights for multiple states in the Western United States to be $91 per acre foot (or 6% of the price) of water traded. Comparing this result to Colby (1990), while they estimate costs of application and legal fees, I show that search frictions can impose significantly larger efficiency losses compared to one time transaction costs.

2.7 Conclusion

In recent years tradeable permit markets have received significant attention as a solution to environmental and natural resources problems at global, national and regional scales. However, our experiences with them have been very mixed. While markets like fishing quota markets have been successful

[9] As a result I end up with 182 individuals that could trade with another partner.

(Newell et al., 2005), others like water quality trading markets have been relatively unsuccessful in achieving their goals (Hahn and Hester, 1989a). Thus it is very important to understand the performance of existing markets in reallocating resources. In this paper I studied the performance of a local informal market by answering two main questions that have not been answered before. The findings in this paper are also of interest to similar permit markets.

First, I find evidence regarding the performance of the market in reallocating groundwater extraction in the direction predicted. I find that while sellers with higher SDF are more likely to sell their rights, this does not hold for buyers. Since the market structure is unidirectional, in the sense that irrigated acres for the trades that increase stream depletion need to be prorated while irrigated acres remain the same for the trades where stream depletion decreases, these findings suggest that the market provides the expected incentives to the buyers and sellers. Furthermore, the results suggest that the presence of search frictions and transaction costs can negatively affect the probability of trade for buyers with lower SDF. This study is the first that finds empirical evidence related to the successful performance of a trading system with complex trading ratios.

Second, the results suggest that the presence of search costs can affect the efficiency of the market by affecting the efficiency of trades that did take place. This is important because most previous studies (Kerr and Maré, 1998; Gangadharan, 2000) have mainly focused on loss of efficiency due to lower participation and not on the trades that had taken place with potentially suboptimal trading partners. Chong and Sunding (2006) explain that most of the studies on water markets are ex-ante predictions of their performance and since they do not consider restrictions and transaction costs, they allow for more trading activity than can happen in practice[10]. We further add to their argument that studies that do not consider multiple sources of transaction costs may underestimate loss of efficiency even within the trades that take place.

Finally, the problem of search costs in tradeable permit markets seems to be due to paucity of information about potential buyers and sellers. We suggest that the presence of "match-makers" that charge a price less than

[10] For an example look at Vaux and Howitt (1984).

cost of search per unit of permit can significantly increase the efficiency of the market.

Two points are worth noting here. First, I have focused on the loss of efficiency in the intensive margin of trade within the trades that have taken place. The other portion of efficiency loss from search frictions is the loss due to trades not taking place. While I provide an upper bound for the former, it is important to note that this value does not include efficiency loss at the extensive margin of trade. Second, the purpose of this study is to focus on the cost-effectiveness of a tradeable permit market. It should be noted that while I show evidence for loss of efficiency within the market under study, this evidence is not enough to draw conclusions regarding the performance of other policies. While search frictions may not exist in other forms of policies, other transaction costs may produce larger losses in efficiency.

2.8 Tables and Figures

Table 2.1: Summary statistics for acres for which water rights were sold

Statistic	N	Mean	St. Dev.	Min	Max
Acres sold	92	56.775	55.083	0.500	261.580
distance from buyer (mi)	92	11.796	15.787	0.033	66.525
Stream depletion factor	92	64.551	27.715	1.000	96.000
Ratio of certified acres within 2 miles	92	0.326	0.175	0.022	0.757
Static water level (ft)	92	63.743	72.604	4.000	257.000
Pumping water level (ft)	92	103.361	83.540	4.000	340.000
Depth of well (ft)	92	221.121	122.320	10.000	600.000
Low soil quality	92	0.533	0.502	0	1
Medium soil quality	92	0.217	0.415	0	1
High soil quality	92	0.250	0.435	0	1
Average monthly precipitation (in)	92	0.053	0.017	0.027	0.073
Corn price (cents per bu)	92	551.842	134.803	219.215	685.489
Diesel price (US$ per gal)	92	3.485	0.616	2.393	3.965

Table 2.2: Summary statistics for acres for which water rights were bought

Statistic	N	Mean	St. Dev.	Min	Max
Acres bought	91	59.015	55.235	0.500	261.580
distance from seller (mi)	91	11.922	15.828	0.033	66.525
Stream depletion factor	91	49.876	24.696	6.439	93.000
Ratio of certified acres within 2 miles	91	0.395	0.179	0.005	0.765
Static water level (ft)	91	92.005	72.808	4.000	296.000
Pumping water level (ft)	91	134.593	85.652	4.000	375.000
Depth of well (ft)	91	282.868	118.727	40	495
Low soil quality	91	0.352	0.480	0	1
Medium soil quality	91	0.505	0.503	0	1
High soil quality	91	0.143	0.352	0	1
Average monthly precipitation (in)	91	0.053	0.017	0.027	0.073
Corn price (cents per bu)	91	553.698	134.361	219.215	685.489
Diesel price (US$ per gal)	91	3.496	0.610	2.393	3.965

Table 2.3: Results of logit regressions for sellers and buyers

	seller		buyer	
	(1)	(2)	(3)	(4)
Stream depletion factor	0.022***	0.022***	0.002	0.002
	(0.006)	(0.006)	(0.005)	(0.005)
Diesel price	−0.713		−0.626	
	(0.468)		(0.471)	
Corn Price	0.005**		0.005**	
	(0.002)		(0.002)	
Annual precipitation	−16.409**		−16.553**	
	(6.988)		(6.997)	
Pump rate	−0.001***	−0.001***	0.0005***	0.0005***
	(0.0002)	(0.0002)	(0.0001)	(0.0001)
Static water level	0.002	0.002	−0.002	−0.002
	(0.002)	(0.002)	(0.002)	(0.002)
High soil quality	−0.100	−0.103	1.665***	1.665***
	(0.274)	(0.275)	(0.382)	(0.382)
Medium soil quality	−0.840***	−0.840***	1.929***	1.929***
	(0.289)	(0.289)	(0.291)	(0.291)
Constant	−4.661***	−6.750***	−6.013***	−7.929***
	(1.088)	(0.779)	(1.004)	(0.650)
Year dummies?	No	Yes	No	Yes
Observations	11,860	11,860	22,443	22,443
Log Likelihood	−500.750	−491.229	−529.119	−520.028
Akaike Inf. Crit.	1,019.501	1,008.458	1,076.238	1,066.056

Note: *p<0.1; **p<0.05; ***p<0.01

Table 2.4: Marginal effects from logit regressions for sellers and buyers

	seller		buyer	
	(1)	(2)	(3)	(4)
Stream depletion factor	0.0001	0.0001	0.000003	0.000003
Diesel price	-0.004		-0.001	
Corn price	0.00003		0.00001	
Average monthly precipitation	-0.085		-0.036	
Pump rate	-0.00000	-0.00000	0.00000	0.00000
Static water level	0.00001	0.00001	-0.00000	-0.00000
High soil quality	-0.001	-0.0004	0.008	0.007
Medium soil quality	-0.004	-0.003	0.009	0.008

Table 2.5: Effects of quantity traded on physical distance using OLS and Heckman 2-step regressions for sellers

	OLS		*Heckman selection*	
	(1)	(2)	(3)	(4)
Acres sold	0.058**	0.088***	0.058**	0.089***
	(0.027)	(0.025)	(0.028)	(0.026)
Stream depletion factor	-0.234***	-0.184***	-0.253***	-0.224***
	(0.061)	(0.058)	(0.088)	(0.082)
Difference in stream depletion factor	0.295***	0.233***	0.299***	0.240***
	(0.067)	(0.062)	(0.082)	(0.078)
Ratio of certified acres	-3.788	-7.465	-2.968	-5.727
	(9.579)	(9.423)	(9.065)	(8.458)
Corn Price	-0.041*		-0.046	
	(0.024)		(0.031)	
Diesel price	11.765**		12.423**	
	(5.363)		(5.851)	
Average monthly precipitation	-0.352		9.687	
	(89.468)		(107.522)	
Constant	0.516	14.571**	7.995	33.690
	(12.215)	(5.925)	(29.823)	(30.457)
Year dummies?	No	Yes	No	Yes
Observations	92	92	11,860	11,860
R^2	0.341	0.459	0.342	0.462
Adjusted R^2	0.287	0.385	0.279	0.380
ρ			-0.201	-0.439
Inverse Mills Ratio			-2.6 (9.4)	-5.57 (8.5)
Residual Std. Error	13.335	12.384		
F Statistic	6.2***	6.17***		
Note:		*p<0.1; **p<0.05; ***p<0.01		

Table 2.6: Effects of quantity traded on physical distance using OLS and Heckman 2-step regressions for buyers

	OLS		*Heckman selection*	
	(1)	(2)	(3)	(4)
Acres bought	0.044	0.067^{**}	0.045	0.071^{***}
	(0.032)	(0.031)	(0.028)	(0.027)
Stream depletion factor	-0.279^{***}	-0.222^{***}	-0.267^{***}	-0.193^{***}
	(0.077)	(0.074)	(0.064)	(0.064)
Difference in stream depletion factor	0.072	0.092	0.096	0.126^{*}
	(0.080)	(0.069)	(0.078)	(0.071)
Ratio of certified acres	-0.737	-5.273	7.691	5.155
	(6.840)	(6.876)	(9.961)	(9.463)
Corn Price	-0.050^{**}		-0.040	
	(0.025)		(0.028)	
Diesel price	13.901^{**}		12.306^{**}	
	(5.541)		(5.607)	
Annual monthly precipitation	-16.833		-83.291	
	(90.992)		(111.169)	
Constant	2.097	16.615^{**}	-24.749	-34.291
	(12.286)	(7.201)	(22.356)	(23.574)
Year dummies?	No	Yes	No	Yes
Observations	91	91	22,443	22,443
R^2	0.348	0.438	0.364	0.472
Adjusted R^2	0.293	0.360	0.302	0.391
ρ			0.619	0.806
Inverse Mills Ratio			9.6 (6.4)	14.3^{**} (6.2)
Residual Std. Error	13.307	12.660		
F Statistic	6.334^{***}	5.607^{***}		

Note: *p<0.1; **p<0.05; ***p<0.01

Table 2.7: OLS regressions of distance for sellers when quantity is not predetermined

	Reg 1[a]		Reg 2[b]	
	(1)	(2)	(3)	(4)
Acres sold	0.062**	0.093***	0.088***	0.113***
	(0.029)	(0.028)	(0.030)	(0.028)
Corn Price	-0.034		-0.029	
	(0.027)		(0.030)	
Diesel price	11.539**		9.555	
	(5.476)		(6.047)	
Monthly precipitation	-59.931		-29.750	
	(103.910)		(111.276)	
Difference in stream	0.174**	0.157**	0.189**	0.135*
depletion factor	(0.082)	(0.077)	(0.086)	(0.081)
Ratio of irrigated	0.744	1.719	-3.017	-9.262
acres	(9.686)	(9.177)	(9.613)	(8.999)
Buyer's total depth	0.027*	0.020		
	(0.014)	(0.014)		
Medium soil quality	-6.259*	-8.047**		
(buyer)	(3.532)	(3.507)		
High soil quality	-5.826	-8.004*		
(buyer)	(4.830)	(4.561)		
Pump rate (buyer)	0.008***	0.002		
	(0.002)	(0.003)		
Difference in total			0.007	0.006
depth			(0.012)	(0.011)
Difference in pump			-0.002	0.001
rate			(0.002)	(0.002)
Difference in soil			-0.825	-1.584
quality			(1.907)	(1.763)
Constant	-25.569*	-2.441	-11.615	0.648
	(13.397)	(8.208)	(13.366)	(7.989)
Year dummies?	No	Yes	No	Yes
Observations	91	91	91	91
Residual Std. Error	12.853	12.021	13.831	12.524

Note: *p<0.1; **p<0.05; ***p<0.01

[a] Reg 1 includes buyers' characteristics

[b] Reg 2 includes the difference between buyer and seller characteristics

Table 2.8: OLS regressions of quantity traded for sellers when quantity is not predetermined

	Reg 1[a]		Reg 2[b]	
	(1)	(2)	(3)	(4)
Corn Price	-0.021		-0.020	
	(0.101)		(0.111)	
Diesel price	10.816		13.111	
	(20.674)		(22.558)	
Monthly precipitation	301.819		350.292	
	(392.769)		(415.971)	
Difference in stream depletion factor	0.194	0.213	0.158	0.228
	(0.309)	(0.311)	(0.322)	(0.334)
Ratio of irrigated acres	-87.876**	-82.966**	-121.884***	-110.517***
	(35.016)	(35.637)	(32.994)	(35.141)
Buyer's total depth	0.176***	0.179***		
	(0.050)	(0.052)		
Medium soil quality (buyer)	-17.057	-12.332		
	(13.275)	(14.205)		
High soil quality (buyer)	-3.690	0.640		
	(18.304)	(18.510)		
Pump rate (buyer)	0.005	0.015		
	(0.009)	(0.011)		
Difference in total depth			-0.041	-0.036
			(0.044)	(0.045)
Difference in pump rate			0.003	-0.001
			(0.008)	(0.009)
Difference in soil quality			-2.490	-1.431
			(7.138)	(7.336)
Constant	-4.543	14.015	39.815	56.379*
	(50.758)	(33.281)	(50.041)	(32.630)
Year dummies?	No	Yes	No	Yes
Observations	91	91	91	91
Residual Std. Error	48.720	48.801	51.865	52.179

Note: *p<0.1; **p<0.05; ***p<0.01

[a] Reg 1 includes buyers' characteristics

[b] Reg 2 includes the difference between buyer and seller characteristics

Table 2.9: OLS regressions of distance for buyers when quantity is not predetermined

	Reg 1[a]		Reg 2[b]	
	(1)	(2)	(3)	(4)
Acres bought	0.075**	0.091***	0.096***	0.106***
	(0.029)	(0.026)	(0.029)	(0.027)
Corn Price	-0.041		-0.032	
	(0.029)		(0.030)	
Diesel price	10.406*		10.297*	
	(5.892)		(5.987)	
Monthly precipitation	-44.788		-42.834	
	(110.425)		(110.442)	
Difference in stream depletion factor	0.199** (0.081)	0.187** (0.074)	0.200** (0.085)	0.182** (0.080)
Ratio of irrigated acres	5.519 (9.426)	-5.013 (9.452)	5.724 (9.358)	-6.434 (9.882)
Buyer's total depth	0.026*	0.015		
	(0.014)	(0.013)		
Medium soil quality (buyer)	-4.853 (4.114)	-5.601 (3.753)		
High soil quality (buyer)	-3.889 (3.668)	-7.875** (3.441)		
Pump rate (buyer)	0.002	0.001		
	(0.003)	(0.002)		
Difference in total depth			-0.006 (0.011)	-0.004 (0.011)
Difference in pump rate			0.003 (0.002)	0.00004 (0.002)
Difference in soil quality			0.082 (1.935)	1.435 (1.829)
Constant	-16.382	2.016	-15.932	-1.161
	(13.677)	(8.270)	(13.417)	(7.866)
Year dummies?	No	Yes	No	Yes
Observations	91	91	91	91
Residual Std. Error	13.481	12.200	13.764	12.757

Note: *p<0.1; **p<0.05; ***p<0.01

[a] Reg 1 includes sellers' characteristics

[b] Reg 2 includes the difference between buyer and seller characteristics

Table 2.10: OLS regressions of quantity traded for buyers when quantity is not predetermined

	Reg 1[a]		Reg 2[b]	
	(1)	(2)	(3)	(4)
Corn Price	0.069		0.042	
	(0.113)		(0.113)	
Diesel price	-6.710		2.661	
	(22.710)		(22.879)	
Monthly precipitation	300.095		287.186	
	(424.540)		(420.885)	
Difference in stream depletion factor	0.682**	0.665**	0.427	0.440
	(0.302)	(0.309)	(0.322)	(0.329)
Ratio of irrigated acres	-109.329***	-102.073**	-112.060***	-104.059**
	(34.260)	(38.995)	(33.556)	(39.448)
Buyer's total depth	0.075	0.082		
	(0.052)	(0.054)		
Medium soil quality (buyer)	-4.370	-3.336		
	(15.856)	(16.152)		
High soil quality (buyer)	-16.632	-10.828		
	(14.023)	(14.761)		
Pump rate (buyer)	0.005	0.005		
	(0.010)	(0.011)		
Difference in total depth			0.059	0.053
			(0.043)	(0.044)
Difference in pump rate			-0.001	0.001
			(0.008)	(0.009)
Difference in soil quality			3.860	2.249
			(7.385)	(7.617)
Constant	41.875	30.895	42.777	43.572
	(52.537)	(35.430)	(51.060)	(32.396)
Year dummies?	No	Yes	No	Yes
Observations	91	91	91	91
Residual Std. Error	51.988	52.524	52.604	53.145

Note: *p<0.1; **p<0.05; ***p<0.01

[a] Reg 1 includes sellers' characteristics

[b] Reg 2 includes the difference between buyer and seller characteristics

Figure 2.1: Map of Natural Resources Districts in Nebraska

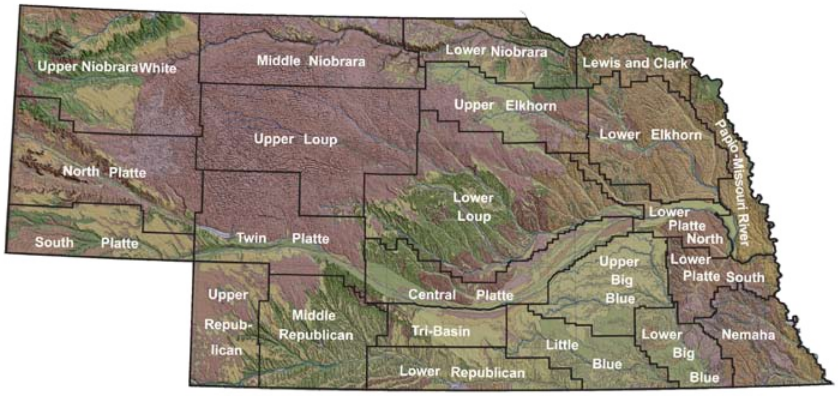


Figure 2.2: Map of the Twin Platte Natural Resources District

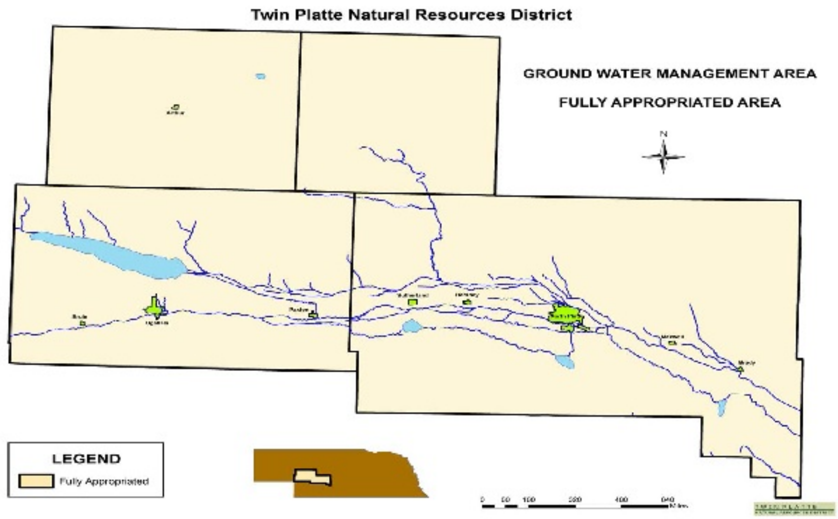


Figure 2.3: Distribution of distance between buyers and sellers in trades

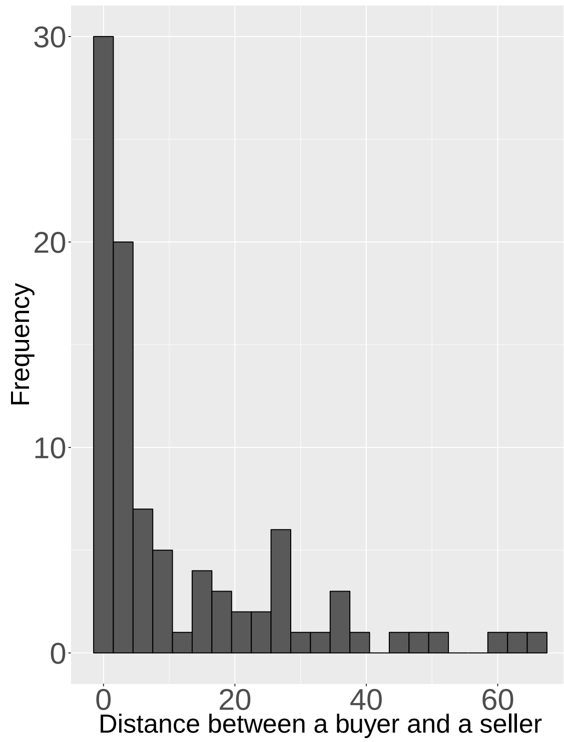
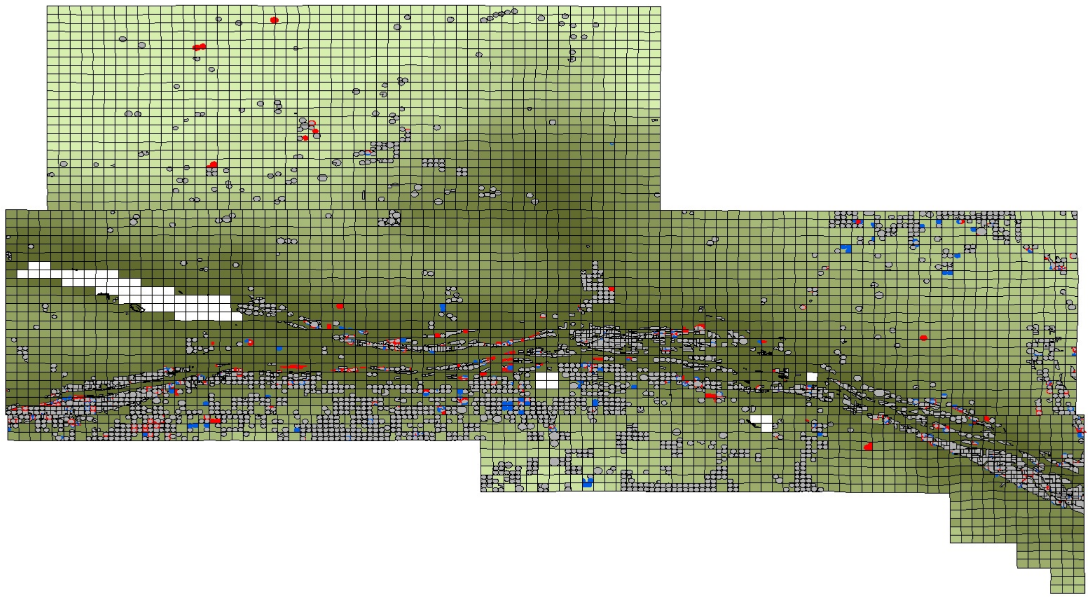


Figure 2.4: Distribution of sold (red), bought (blue) and irrigated (grey) acres over sections with stream depletion factors: high (dark) to low (light)



CHAPTER 3

EFFECTS OF INSTANTANEOUS GROUNDWATER AVAILABILITY ON IRRIGATED AGRICULTURE AND IMPLICATIONS FOR AQUIFER MANAGEMENT

3.1 Introduction

Groundwater aquifers are important sources of water supply for irrigated agriculture. Physical aquifer characteristics impose limitations on the rate that a farmer can extract groundwater during the growing season. The existing economics literature and current policies do not take into account the effect of limited extraction rates on farmers' irrigation decisions. This paper has two objectives. First, to develop an analytical framework to study the effects of maximum available groundwater flow rate from an aquifer on a profit maximizing farmer's irrigation decisions about the number of irrigated acres and expected groundwater application per acre. Second, to analyze whether maximum available groundwater flow rate is important for determining the effectiveness and equity of different aquifer management policies.

Groundwater is a major source of water supply for agricultural production. It provides water for about 40% of the irrigated land in the world (Siebert et al., 2010). Groundwater aquifers provide a reliable and flexible source of water supply for very sophisticated production systems like those of the American West, while also providing food security for some of the densely populated rural areas of developing countries such as India and China (Shah, 2014). However, the reliability and flexibility of groundwater aquifers has resulted in rapid depletion of the aquifers in many groundwater-dependent agricultural areas. Changes in aquifer levels have put pressure on irrigated agriculture and raised concerns regarding the effect of declining aquifer levels and groundwater availability on irrigated agriculture and on the types of policies required to protect the aquifers (OECD, 2015; Peterson et al., 2003).

Unfortunately, there exists a disconnection between agronomic and engineering literatures and economics literature on the effects of physical aquifer characteristics on crop production. Most existing economic studies of groundwater management (Gisser and Sanchez, 1980; Caswell and Zilberman, 1986; Knapp and Olson, 1995) consider the aquifer as a stock of groundwater. These studies assume that the aquifer affects farmer decisions only through depth to the groundwater table and marginal pumping cost (Upendram, 2009). An implicit assumption in these studies is that the maximum possible extraction rate from the aquifer is infinite and a farmer can continuously meet crop water demand during the growing season. Agronomic and engineering studies, however, show that physical aquifer characteristics affect maximum rates of groundwater extraction from an aquifer and that the maximum extraction rate can affect crop yield. Since the goal of most aquifer management policies is to stabilize aquifer levels or slow down aquifer depletion, overlooking the effect of instantaneous groundwater availability on irrigation decisions through its effects on crop yield could result in miscalculating the effectiveness of studied policies. Furthermore, because farmers' access to instantaneous groundwater flow can vary significantly within a basin, these policies ignore the heterogenous effect they can have among farmers.

In this study, we introduce an analytical framework of a profit-maximizing farmer to address the effect of instantaneous groundwater availability, or well capacity, on irrigation decisions on the extensive and intensive margins. We then explore the implication of heterogeneity among farmers in terms of access to groundwater within a growing season for the impacts of climatic changes and pricing policies on irrigation decisions among farmers.

The analytical results show that the effect of instantaneous groundwater availability on intensive and extensive margin decisions are nonlinear. We find a well capacity (the switching point) above or below which irrigation decisions are different. This switching point is a function of crop water demand, irrigation technology, soil characteristics, weather conditions, and prices of water (or energy) and crops. For well capacities above the switching point, a profit-maximizing farmer can irrigate their entire parcel while adjusting the intensive margin for changes in maximum groundwater flow rate. A profit maximizing farmer with lower well capacity than the switching point, however, will adjust their irrigated acres to provide enough capacity to meet crop water demands during the critical stages of the growing season. These results have two major implications: 1) price elasticity of demand is not monotonic among profit maximizing farmers with different well capacities, and farmers with some intermediate range of well capacities are most responsive to the changes in price of water; and 2) the effect of changes in average weather conditions may not be monotonic among farmers either, with intermediate capacity wells the most vulnerable to drier weather conditions. Finally, using well level data from the Upper Republican Natural Resources District in Nebraska, we explore the effect of aquifer heterogeneity on cost-effectiveness and distributional effects of four different policies that intend to reduce consumptive water use. These policies include a pumping tax, an acreage tax, and two policies that limit irrigated acres. The policy analysis shows that different policies can result in different responses on the intensive and extensive margins among farmers. While a pumping tax is the cost-effective policy to reduce irrigation in this case, it mainly affects farmers with medium and high capacity wells. On the other hand, a tax on the irrigated acres primarily affects low capacity wells. Thus in cases where targeting low capacity wells provides higher benefits for the aquifer, or when lower well capacities are a result of historical over-pumping by farmers, an acreage tax might be the preferred policy. However, in cases where lower well capacities are merely a result of underlying aquifer characteristics (e.g. uneven bedrock levels), a pumping tax might be the preferred policy.

This paper contributes to the literature in several ways. First, most economics studies of groundwater management in agriculture do not fully take into account the effects of physical aquifer characteristics on farmers' irrigation decisions. Some previous studies (Brozović et al., 2010; Guilfoos et al., 2013) have analyzed the effects of aquifer characteristics on the extent of spatial externalities among farmers. However, this literature does not include the effects of groundwater flow rate on irrigation decisions. While some studies suggest that daily water availability affects farmers' irrigation decisions (e.g. Pfeiffer and Lin (2014)), they do not take into account the effect of aquifer characteristics on maximum groundwater flow rate. This study is the first to provide an analytical framework to study the effects of maximum groundwater flow rate on farmers' irrigation decisions.

We also contribute to studies on the effects of heterogeneity among farmers on irrigation decisions. Caswell and Zilberman (1986) and Lichtenberg (1989) have looked at the effect of soil properties and depth to water on irrigation decisions. This study adds maximum available groundwater flow rate as a source of heterogeneity among farmers and shows that this source of heterogeneity can be important on the extensive and intensive margins. We further contribute to the literature on the effectiveness and distributional effects of aquifer management policies. Feinerman and Knapp (1983) show that pumping taxes and quotas can achieve allocation efficiency; however, they will have different distributional effects on groundwater users. We add another layer to the policy discussion by showing that different policies could have differential effects on different types of farmers based on their access to maximum groundwater flow rate.

3.2 Previous Studies

3.2.1 Agronomic Studies

Agronomic and extension studies suggest that crop water demand depends on evapotranspiration (ET) and is distributed over the entire growing season (Lamm et al., 2007). Crop water demand is higher and crop yield is more susceptible to water stress in critical stages of growth (Rogers et al., 2015; Schneekloth et al., 2009; Martin et al., 1984). Thus, it is important to be able to meet crop water demand during the critical stages of crop growth (Martin and Gilley, 1993). If daily water demand is not satisfied over the critical stages of the growing season, the crop canopy might die, at which point adding more water does not increase yield. Thus, deficit irrigation during the critical stages of the growing season can result in a negative impact on crop yield (Andales, 2009). This literature also suggests that every crop needs a minimum amount of evapotranspiration in order to produce harvestable biomass. This minimum amount is called the threshold ET and it is different among crops. In wet years, this amount is provided by precipitation. However, in dry years, irrigation needs to provide the required water to meet the threshold (Rogers et al., 2015). There is also a plateau of yield. When a crop reaches maturity, adding more water does not significantly increase yield.

On the other hand, instantaneous supply of groundwater is limited by groundwater levels and physical aquifer characteristics such as hydraulic conductivity and specific yield, which are measures of the flow of groundwater in the aquifer (Hecox et al., 2002). Instantaneous groundwater supply from a well is often referred to as well capacity and is defined as the maximum volume of water that can be extracted in a given time (e.g. gallons per minute). With limited instantaneous groundwater availability, the ability to meet crop water demand during the critical periods in the entire parcel decreases, which can result in crop stress and loss of yield (Schneekloth and Andales, 2009). However, the ability to meet crop water demand during critical stages of the season is not exogenous. A farmer can allocate the number of irrigated acres at the beginning of the growing season in order to meet water demand. Thus, the potential crop yield per irrigated acre depends on the maximum application rate per acre (O'Brien et al., 2001), which is defined as well capacity divided by the number of irrigated acres.

Finally, previous studies suggest that weather can affect irrigation decisions in two ways. First, in a dry year, a farmer needs to apply more water during the season to supplement reduced precipitation and attain the same crop yield as in a wet year. Second, in a dry year, a farmer needs to allocate higher maximum application rates per acre to provide the crop with enough soil moisture during the critical stages of the growing season. In other words, in a dry year, a farmer that allocates low maximum application rate per acre, with the same amount of water applied, will get a lower crop yield than a farmer that allocates high maximum application rate per acre (Lamm, 2004; Lamm et al., 2007) because they can not meet demand during critical stages of the season.

3.2.2 Economic Studies

In efforts to incorporate these characteristics into economic models, most existing studies have focused on the optimal irrigation scheduling within a growing season (Shani et al., 2004; Hornbaker and Mapp, 1988; Feinerman and Falkovitz, 1997; Yaron and Dinar, 1982). A common conclusion among most of these studies is that applying water during the critical stages of the growing season is an important factor that affects crop growth and determining harvestable crop yield. However, they have not considered instantaneous groundwater supply limitations. Recently there have been several studies that include limitations on the instantaneous groundwater availability, most of which focus on numerical analysis.

Peterson and Ding (2005) studied the effect of irrigation efficiency on water saving by considering well capacity and risk preferences. They broke down the production function into four stages to capture the intra-seasonal nature of crop water demand and irrigation decisions. They find that water application at different stages of crop growth has different effects on crop yield. Interestingly, for all irrigation technologies, under a higher well capacity, farmers apply less water at early stages and apply more water later in the season resulting in higher seasonal application regardless of their risk preferences.

Upendram (2009) studied the risk-efficient choice of crop, technology and irrigation timing for a risk-averse farmer in western Kansas. They used management allowed deficit (MAD) as a decision variable that determines irrigation timing. MAD is the amount of deficit in the soil profile that triggers irrigation. Their results show that well capacity is an important factor for the choice of irrigation technology and irrigation strategy.

Both Peterson and Ding (2005) and Upendram (2009) assume a fixed number of irrigated acres in their models. This is a limitation because allocating irrigated acres at the beginning of the season is an endogenous decision based on well capacity. Foster et al. (2014) showed that not only the decision on the soil moisture target, which is similar to MAD, but also number of irrigated acres matter for crop yield and water use. They show that with high well capacities seasonal groundwater availability can be a binding factor, while with low well capacities well capacity is a limiting factor that can limit the number of irrigated acres and groundwater application. Foster et al. (2015a) further show that well capacity is a more important determinant of farmers' decisions on the number of irrigated acres, seasonal water use and profits than depth to water.

While some empirical studies claim that groundwater availability during the critical stages of the growing season matters, they do not explicitly account for limitations in instantaneous groundwater availability in their analysis (Pfeiffer and Lin, 2014). There have been a few studies that, study the effects of instantaneous groundwater availability on irrigation decisions and land prices. Using a hedonic approach, Brozovic et al. (2010) estimated the value of groundwater for Chase County in Nebraska. Their results show that well capacity is an important determinant of the price of an irrigated parcel. This finding suggests that limitations on instantaneous groundwater availability can affect irrigation decisions. Collie (2015) explicitly asked whether well capacity affects irrigation decisions. Using an instrumental variable approach they show that well capacity affects irrigation decisions on the extensive and intensive margins. Specifically, they show that for the case of Kansas, farmers with higher well capacities irrigate more acres, and grow crops that are more water intensive, suggesting that they irrigate larger quantities per acre.

Finally, there have also been few studies that included analytical frameworks with groundwater supply limitations included in the model. Wang and Nair (2013) study the effect of limitations on seasonal groundwater availability on irrigation decisions on the intensive and extensive margins. They argue that seasonal limitations could be a result of limited well capacity. They show that when seasonal groundwater supply is limited, a farmer will extract all the available seasonal supply and does not conserve groundwater, and as a result is unresponsive to changes in price of water. However, their model does not consider intra-seasonal effects of well capacity on crop yield and irrigation decisions and merely models well capacity limitations as a seasonal limitation on groundwater availability.

Peterson and Saak (2013) is the only study that considers the effect of well capacity on crop revenue in an analytical framework. They studied the difference in the steady state groundwater levels under competitive and planning conditions with different aquifer thicknesses. In their model, revenue is a function of water application and saturated thickness suggesting that as saturated thickness decreases, well capacity decreases and as a result, revenue decreases. Their results suggest that well capacity does affect the difference in aquifer levels between planning and competitive scenarios. A limitation of their model is that it does not consider the intensive and extensive margin decisions of a farmer. Not considering the decisions on the intensive and extensive margins explicitly can result in overestimating water use and profits when well capacity is low.

3.3 Analytical Framework

In practice, irrigation decisions are made in two stages. At the beginning of a growing season, a farmer allocates irrigated acres (extensive margin) based on water availability. During the growing season, they will apply water (intensive margin) to meet daily crop water demand. I develop a production function that captures both the inter-seasonal and intra-seasonal nature of irrigation decisions. The production function, $G(\frac{X}{A}, \epsilon)\Phi(u, \mu + \epsilon, \sigma)$, is composed of two parts: an intra-seasonal part and an inter-seasonal part. The intra-seasonal part of the function, $\Phi(u, \mu + \epsilon, \sigma)$, provides a relationship between expected seasonal groundwater application per acre (irrigation depth), u, and expected crop yield under current climate conditions assuming no limitations on groundwater availability. This part of the production function follows a cumulative distribution function (CDF). Previous literature shows that the intra-seasonal irrigation decision in a stochastic environment can be characterized by an optimal soil moisture target strategy (Shani et al., 2004; Mieno, 2014). In a stochastic environment, any soil moisture target will result in an expected groundwater application and an expected crop yield. A farmer can thus set a soil moisture target based on the distribution of precipitation to maximize expected crop yield given expected seasonal water use. The $\Phi(u, \mu + \epsilon, \sigma)$ function is the solution to the stochastic intra-seasonal optimization of the farmer for each soil moisture target. While the optimization has not been solved analytically in this chapter, the process is similar to Cropper (1976) in that a CDF is used to model a stochastic process. This characterization allows me to provide tractable closed form solutions.

The CDF also includes biophysical characteristics of the crop, soil and irrigation technology, μ and σ under current climatic conditions. A larger μ corresponds to a crop with higher demand for water, while higher σ can be used to show a crop that is more sensitive to declines in seasonal water application so that as seasonal water application decreases from the yield maximizing level, crop yield decreases more. Similarly, more efficient technologies or different soil types can affect μ or σ. The intra-seasonal part of the production function also includes a parameter that captures changes in climate, ϵ. $\Phi(.)$ provides crop yield under existing stochastic climate conditions, while ϵ can be thought of as an index that shifts the production function, e.g. due to climatic changes. A higher ϵ shows a drier climate. In a drier climate, for a given well capacity and irrigated acres, the expected seasonal application needs to be higher to achieve the same expected crop yield figure 3.1b).

Furthermore, a CDF form provides us with several features that map to crop water production function. First, the lower tail of the CDF function can be interpreted as the threshold ET below which crop yield is zero. Second, the upper tail of the CDF function can be interpreted as the plateau of crop yield when the crop reaches maturity and adding more water does not significantly increase crop yield. Finally, it provides us with the ability to captures the effect of a change in weather on crop yield. It suggests that the marginal value of water is highest at some intermediate amount of water applied and not for the first unit of water applied. This non-monotonicity explains the intra-seasonal nature of crop growth.

Limitations on instantaneous groundwater availability can affect crop yield negatively by affecting a farmer's ability to meet crop water demand during the growing season. The second component of the production function, $G(\frac{X}{A}, \epsilon)$, captures the effect of instantaneous groundwater availability on crop yield. It includes the maximum application rate, $(\frac{X}{A})$, which is the ratio of well capacity, X, over irrigated acres, A. Maximum application rate directly affects the seasonal production function, and is an important part of farmers' decision making (New et al., 2000). With high maximum application rates, a farmer is able to meet crop water demand over the entire growing season. As maximum application rate decreases a farmer's ability to meet crop water demand optimally during the critical stages of the growing season where the demand is the highest also decreases. As a result, attainable (expected) crop yield decreases. This effect is more significant in a dry climate. In wetter climates, a reduction in maximum application rate does not significantly affect expected crop yield since rainfall can supplement for irrigation and soil moisture levels are higher. However, in a drier climate, a reduction in maximum application rate could result in not being able to meet crop water demand during the critical stages of the season and significant loss of crop yield. Another way to interpret this relation is that for high well capacities a farmer is able to buffer for any weather condition. However, with low well capacities, the potential crop yield significantly depends on the weather conditions during the growing season (figure 3.1a). The farmer makes the decision regarding the irrigated acres at the beginning of the growing season. When instantaneous groundwater supply is limited, an increase in number of irrigated acres can decrease maximum daily application rate which can negatively affect crop yield.

$G(\frac{X}{A}, \epsilon)$ can be thought of as a penalty function with the domain $[0, 1)$. The properties of the $G(.)$ function are: $G_1(\frac{X}{A}, \epsilon) \geq 0$, $G_{11}(\frac{X}{A}, \epsilon) \leq 0$, and $G_2(\frac{X}{A}, \epsilon) \leq 0$, where $G_1()$ and $G_{11}()$ are first and second partial derivatives with respect to the first argument, and $G_2()$ is the first order partial derivative with respect to ϵ. Finally, for every ϵ, $G(0, \epsilon) = 0$ and $\lim_{\frac{X}{A} \to \infty} G(\frac{X}{A}, \epsilon) = 1$. These properties maintain that for very high maximum daily groundwater availability, the farmer can buffer for dry weather and crop yield will not suffer. However, as maximum daily availability of groundwater decreases, the effect of daily groundwater availability on crop yield increases at an increasing rate because the farmer is not able to meet crop water demand during the critical stages of the season when demand is high. This assumption states that intra-seasonal profit maximizing strategies depend on the maximum amount of water that a farmer can extract from a well. Consequently, we assume that there does not exist an irrigation scheduling and intra-seasonal allocation that can provide the same crop yield with lower maximum daily application rate per acre. This assumption suggests that if a farmer reallocates water from the periods of critical demand, crop yield will decrease. It is important to note that this does not mean that there exists a single profit maximizing strategy within the season, but rather that all irrigation strategies with lower maximum daily application rates provide weakly lower profits. Based on the characterizations of the inter and intra-seasonal parts of the production function, we can solve the problem of allocating extensive and intensive margins simultaneously. A farmer maximizes the expected profit by allocating irrigated acres and groundwater application per acre for a given climate:

$$
\begin{aligned}
\underset{A,u}{\text{Max}} \quad & A\left\{G(\frac{X}{A},\epsilon)\Phi(u,\mu+\epsilon,\sigma)-\Gamma(Y)u\right\} \\
\text{subject to} \quad & Au \leq h(X) \\
& A \leq 1 \\
& A, u \geq 0
\end{aligned}
\tag{3.1}
$$

where Y is saturated thickness that shows the aquifer level and $\Gamma(Y)$ is marginal cost of pumping a unit of water with $\Gamma'(Y) > 0$, i.e. as aquifer levels decline, marginal cost of pumping groundwater increases. For simplicity we are assuming that well capacity does not affect the cost of pumping. In practice, with lower wells a farmer needs to irrigate more hours to achieve the same irrigation depth. Thus pumping cost is higher with lower well capacities. Also, as mentioned in the previous Section, saturated thickness affects well capacity. However, in this model, well capacity and saturated thickness are considered separately in order to explain the effects of instantaneous groundwater availability on irrigation decisions. $G(\frac{X}{A},\epsilon)\Phi(u,\mu+\epsilon,\sigma)$ is crop yield per acre, or revenue with price of output set to 1. The maximum attainable yield is standardized to 1 in the analytical model. $h(X)$ is the maximum amount of groundwater available during the growing season and is a function of well capacity. It is the integral of the instantaneous amount of groundwater available over the season. In a simple way, it can be thought of as the number of days in a growing season times the maximum daily groundwater available. This is the case when well capacity does not decline during a single growing season, which is usually the case, for example in the American West. In a more general case, well capacity can decline during the season as groundwater is pumped out of the aquifer, for example in hard rock aquifers of India. However, we focus on the case where groundwater availability does not decline over the season. The second constraint in equation 3.1 shows the limit on the proportion of the acres that can be irrigated. It is important to mention that in this model, non-irrigated profits are fixed at zero. This is a simplification in the interest of analytical simplicity and does not affect results in a meaningful way. Given the basic model, we then provide the Lagrangian of the maximization problem:

$$\mathcal{L} = A\Bigg\{G(\frac{X}{A}, \epsilon)\Phi(u, \mu + \epsilon, \sigma) - \Gamma(Y)u\Bigg\} + \lambda_1[h(X) - Au] + \lambda_2[1 - A] \tag{3.2}$$

where λ_1 is the shadow value of adding one unit of water during the season by increasing well capacity and λ_2 is the shadow value of adding an irrigated acre. Since $A = 0$ if and only if $u = 0$, we only focus at the case where $A, u > 0$. Thus, the first order conditions are:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial A} &= \Bigg\{G(\frac{X}{A^*}, \epsilon) - (\frac{X}{A^*})G'(\frac{X}{A^*}, \epsilon)\Bigg\}\Phi(u^*, \mu + \epsilon, \sigma) - \Gamma(Y)u^* - \lambda_1 u^* - \lambda_2 = 0 \\ \frac{\partial \mathcal{L}}{\partial u} &= A^*\Bigg\{G(\frac{X}{A^*}, \epsilon)\Phi'(u^*, \mu + \epsilon, \sigma) - \Gamma(Y) - \lambda_1\Bigg\} = 0 \end{aligned} \tag{3.3}$$

where A^* and u^* are the profit-maximizing levels of intensive and extensive margin decisions for different well capacities. The first term in the first equation shows that keeping everything fixed, adding an acre increases profit due to production in one more irrigated acre, while it decreases profit because adding an acre would reduce maximum daily application rate for the entire parcel. $\{G(\frac{X}{A^*}, \epsilon) - (\frac{X}{A^*})G'(\frac{X}{A^*}, \epsilon)\}$ is always positive because $G(.)$ is concave in maximum daily application rate, suggesting that the positive effect of adding an acre on crop production always outweighs its negative effects from daily groundwater availability. We suppress the star notation for the sake of notational simplicity.

In order to explain the effect of instantaneous groundwater availability on irrigation decisions over the domain of well capacity, $[0, \infty)$, we solve for A and u by decreasing well capacity from infinity to zero and provide the results in three propositions. The first proposition provides the profit-maximizing decisions under infinite well capacity which is the assumption underlying existing economics literature. The following propositions deviate from this condition by looking at well capacity rates less than infinity.

Proposition 1[1]**.** As $X \to \infty$, $A^* = 1$ and $u = u^*_\infty(Y, \mu, \sigma, \epsilon)$.

[1] All proofs are provided in Appendix B.

Proposition 1 shows that when instantaneous groundwater availability reaches infinity, profit-maximizing quantity of water applied is a function of cost of pumping, crop characteristics, technology, soil type and weather. Even though this is a theoretical result, since infinite well capacity does not exist in practice, this is an important result in explaining the effect of instantaneous groundwater availability on irrigation decisions. This proposition suggests that there exists an optimal intensive margin allocation when a profit-maximizing farmer has access to unlimited amounts of water on every day of the irrigation season. From a modeling perspective, this condition is similar to the case considered within the majority of the economics literature where instantaneous groundwater availability does not affect crop yield, and where pumping cost is the only factor affecting irrigation decisions.

Proposition 1 also suggests that under these conditions, the profit-maximizing decision is either to irrigate the entire parcel or irrigate zero acres. Finally, an increase in pumping cost will result in further deficit irrigation, but does not affect the extensive margin decision. The next three propositions explain that if well capacity is finite, daily groundwater availability affects irrigation decision. They further explain how profit-maximizing decisions change if maximum groundwater availability decreases, keeping other parameters fixed.

Proposition 2. For high (finite) well capacities, the optimal decision is to irrigate the entire parcel, $A = 1$, at a rate less than U^*_∞. The application rate per acre decreases as well capacity decreases.

When well capacity is infinite, a farmer can irrigate the whole parcel, apply groundwater optimally over the growing season, U^*_∞, and meet daily crop water demand. As well capacity decreases, maximum daily application rate per acre decreases. With lower maximum daily application rate, the farmer's ability to meet daily crop water demand during the critical stages of the growing season decreases. They can apply the same amount of seasonal water by reallocating the quantity from the peak demand days to off-peak demand days of the growing season (e.g. earlier or later in the growing season). However, the marginal effect of irrigation is lower when applied during the off-peak days of the growing season. As a result, the profit maximizing quantity of groundwater applied per acre decreases. For high well capacities the effect of daily groundwater availability is practically small, because for high well capacities, a small decrease in maximum daily groundwater availability does not significantly affect crop yield. However, for lower well capacities, this effect becomes more significant. This suggests that practically, for very high well capacities, daily groundwater availability does not affect irrigation decisions. For aquifers with high saturated thicknesses, well capacity is practically very high. This might be one reason that earlier studies did not include instantaneous groundwater availability in their models. Proposition 2 also provides the decision rule for high well capacities: as well capacity decreases from infinity, keeping everything else fixed, the profit-maximizing decision is to irrigate the entire parcel and adjust on the intensive margin.

Finally, it is important to notice that the reduction in the amount of water application is not due to seasonal groundwater availability, but rather because of the impact of maximum daily groundwater availability on crop yield. There is limited storage capacity within the soil profile. With this limited storage capacity the farmer is not able to store enough water within the soil profile to meet crop water demand during the critical stages of the growing season. Furthermore, applying more water at the initial periods of crop growth could result in undesirable growth in crop roots that could affect crop yield.

Proposition 3. There exists a well capacity, X_s, where a profit maximizing farmer with a higher well capacity can irrigate their entire parcel, while a profit maximizing farmer with well capacity below X_s will decrease the number of irrigated acres to be able to meet crop water demand during the season. I call the point, the switching point.

At infinite well capacity, the shadow value of adding an acre is positive. As well capacity decreases from infinity, shadow value of adding an acre of irrigated land decreases. At $X_s(\mu, \sigma, \epsilon, Y)$, the shadow value of adding an acre reaches zero. At this point the decision switches from adjusting on the intensive margin to adjusting on the extensive margin, i.e. for well capacities above X_s, the profit maximizing decision is to irrigate the whole parcel and adjust per acre application, while at well capacities below X_s the profit maximizing decision is to adjust proportion of irrigated acres and keep the application rate fixed. The reason is that when well capacity is below X_s, if the farmer irrigates the whole parcel, reduction in maximum daily application rate significantly affects crop yield because the farmer is not able to meet crop water demand effectively during the growing season. As a result, the farmer reduces the proportion of acres irrigated to keep maximum daily application rate, $\frac{X}{A}$, at a minimum, k_{min}. They will not decrease maximum daily application rate and seasonal groundwater application below this point. For lower well capacities, the farmer reduces the proportion of irrigated acres to keep maximum daily application rate at k_{min}. As a result, per acre application rate remains fixed at u_{min} below X_s. $X_s(\mu, \sigma, \epsilon, Y)$ depends on the crop's sensitivity to seasonal and daily water availability, cost of pumping, and climate. A change in any of the factors can affect the switching point.

Existence of the switching point has several implications. First, there exists a well capacity below which a profit-maximizing farmer does not further deficit irrigate below u_{min} with changes in well capacity. This is in contrast to many of the existing literature that do not consider instantaneous groundwater availability as a limitation on production. While the model presented in this chapter is not dynamic, this result can suggest that the response to lower aquifer levels is not always further deficit irrigation. Farmers can adjust irrigated acres as a response to lower saturated thicknesses due to limited daily groundwater availability.

The results also suggest that it is important to consider heterogeneity among farmers in terms of daily groundwater availability due to nonlinearity of the effects of groundwater availability on water use and profits. While the difference in water consumption and profits can be small for high capacity wells, it can be significant for low capacity wells because for a profit-maximizing farmer a low capacity well can irrigate fewer acres compared to high capacity wells.

Finally, our results have implications for water rights allocation policies. While these policies can affect higher capacity wells, they may not affect low capacity wells since farmers with low capacity wells adjust their irrigated acres and water consumption decreases significantly. This might be one possible explanation for why water allocation policies in west Kansas are not a binding constraint for many farmers. For example, in studying the significance of pumping externalities in western Kansas, (Pfeiffer and Lin, 2012) used a farmer's neighboring permit amount as an instrumental variable for determining their pumping quantity. They showed that while the pumping permit is a strong predictor of the amount of groundwater pumped, there is not a one-to-one relationship between them and a one acre-foot increase in permit amount results in 0.3 acre-feet increase in quantity pumped.

While our results show that with lower well capacities groundwater extraction decreases, one concern is whether lower well capacities could result in more water application during the growing season because a farmer is not able to meet crop water demand during the critical stages of the growing season. However, in practice this is not the case because crop canopy is not completely developed at the beginning of the season. More water application in this stage could result in larger soil evaporation which is non-beneficial.

Together, Propositions 1 to 3 show the profit-maximizing levels of irrigated acres (extensive margin) and per acre application rate (intensive margin) over the domain of well capacity $X \in [0, \infty)$. Unlimited capacity or some variations of it are the cases considered within the existing economics literature. Comparing Propositions 2 and 3 to Proposition 1, we can conclude that instantaneous groundwater availability can affect irrigation decisions and profits non-linearly. These results also provide us with a tractable analytical solution so that we can derive comparative statics. Even though the framework is static these results can provide insight and the basis for dynamic analysis. The results suggest that looking at a cross section of data, controlling for other factors, we expect larger irrigated acres and small differences in per acre water application among farms with large well capacities, and variation in the proportion of acres irrigated among low capacity wells.

In proposition 3, I showed that there exists a switching well capacity. The next proposition makes this claim stronger by providing the conditions that we might observe a switching point in irrigation decisions. In order to do so, I define sensitivity to daily water availability as the effect of a change in per acre maximum daily water availability on crop yield. For a given weather, crop j is defined to be more sensitive to daily water availability than crop i if a decrease in per acre maximum daily water availability affects yield of crop j more severely than crop i. Mathematically, $G_j(.)$ has a larger curvature than $G_i(.)$. A crop is not sensitive to daily water availability if a decrease in maximum daily application rate per acre does not affect crop yield, i.e. $G(.)$ is constant.

Proposition 4. Under two conditions we may observe a switching point: (a) when a crop is sensitive to daily water availability; (b) when total seasonal water availability constraint binds.

Condition (a) of Proposition 4 can be thought of as a corollary to Proposition 3. If $G(\frac{X}{A}, \epsilon)$ is not constant, i.e. if daily water availability affects crop yield, a switching point exists. However, the opposite is not necessarily true, i.e. a switching point can exist when a crop is not sensitive to daily water availability. This can happen when the total seasonal water availability constraint binds which is the claim (b) of proposition 4. Proposition 4(b) is similar to what Wang and Nair (2013) show in their paper. They show that there exists a similar switching point when total seasonal water availability is limiting. Their results can be considered a special case of the model studied in this paper when the crop is insensitive to daily water availability. Proposition 4 also explains that models that do not consider sensitivity to daily water availability or limited seasonal water availability do not find a switching point. This is a theoretical proposition that shows the results of the model are general and previous models are special cases of the current model. In practice, daily water availability does affect crop yield. However, even when a crop is sensitive to daily water availability, total seasonal groundwater availability might still become the binding constraint and affect the switching point rather than daily water availability. Proposition 5 provides the condition that seasonal water availability can be binding.

Proposition 5. There exists a sensitivity to daily water availability, $\bar{G}$, above which total seasonal water availability does not bind.

As well capacity decreases from infinity, both total seasonal water availability, $h(X)$, and maximum daily water availability, $\frac{X}{A}$, decrease. Proposition 5 claims that when crop sensitivity to daily water availability is low, for low well capacities, total seasonal water availability will affect irrigation decisions rather than daily groundwater availability. On the other hand, if the crop is "sensitive enough" to daily groundwater availability, the maximum daily application rate per acre will affect the decision. This result makes intuitive sense. If crop yield does not decrease significantly as a result of a decline in maximum daily water available per acre and we can reallocate water from the critical stages of the growing season without any penalty, we reach a point where the seasonal water availability constraint becomes binding. However, in most cases in practice, we expect the daily groundwater availability to affect the switching point rather than seasonal availability. For example, the Food and Agriculture Organization (FAO) recommends a daily water application of 0.24 inches per day (6.1 mm/day), and a seasonal water demand of

19.685 to 31.5 inches (500 to 800 mm) with a growing season of 125 to 180 days for corn. If we divide 25.6 inches by 152.5 days (their average values), we get 0.168 inches per day. This suggests that the effect of daily water availability is higher than seasonal availability. For citrus, however, the daily water demand is 0.15 inches/day (3.85 mm/day) with a growing season of 240 to 365 days and total water demand of 35.4 to 47.24 inches (900-1200 mm). Diving 41.32 inches by 302.5 days, we get 0.168 inches per day. Unlike corn, for citrus seasonal water availability might be the constraint.

In theory, $\bar{G}$, defines a sensitivity to daily water availability above which we do not expect to see total seasonal water availability to affect switching point. Since in practice we expect most crops to be more sensitive than $\bar{G}$, we ignore the constraint on total seasonal water availability.

3.4 An Illustrative Example

In order to depict Propositions 1 to 3, a production function was generated by calibrating the production function introduced in section 3.3 to production functions generated by AQUACROP-OS (Foster et al., 2017), an open source crop simulation model, for corn production in Chase County, Nebraska. The parameters used in this study are provided in table 3.1. We assume that the maximum irrigable land is 130 acres which is the size of a quarter-section center-pivot circle. We also consider a fixed cost for production. The fixed cost is not considered in equation 3.1, but is considered here to provide realistic solutions and does not affect the intuition behind Propositions 1-3. Results are shown in figure 3.2.

We can see that the switching point, considered for Chase County is 28 acre-inches per day or $\approx$ 530 gallons per minute under current climate conditions. The figures show that above the switching point, a profit-maximizing farmer will irrigate their entire parcel (130 acres), while below the switching point they will adjust irrigated acres linearly keeping expected irrigation depth at 16.4 inches. Finally, we can see that heterogeneity in water consumption and profits are smaller above the switching point. Comparing figures 3.2c and 3.2d, we can see that above the switching point even though the application depth does not decrease significantly, profits decline rapidly due to limited groundwater availability during the critical stages of the growing season. We further show the importance of the findings of Propositions 1 to 3, by examining the implications of the heterogeneity in access to instantaneous groundwater supply on irrigation decisions and profits.

3.4.1 Effects of an Increase in Pumping Cost

In this section we study the effects of an increase in pumping cost on irrigation decisions. Since the focus in this paper is on the effect of instantaneous groundwater availability on irrigation decisions and profits, we keep the pumping cost fixed over the domain of well capacity. The analytical analysis, which is provided in Appendix B, focuses on the effect of a marginal change in the cost of pumping on the profit maximizing amount of water applied per acre and the switching point, while the numerical results also include the changes in total water demand across well capacities.

The analytical results show that an increase in pumping cost will decrease water consumption for every well capacity, and will shift the switching point to a higher well capacity. This result suggests that while high capacity wells adjust on the intensive margin as a result of an increase in pumping cost, medium and lower well capacities (well capacities below 30 acre-inches per day) adjust on both the intensive and extensive margins. Specifically, some range of wells above the switching point will not irrigate their entire parcel any more as a result of an increase in pumping cost. The range of well capacities affected depends on the size of the increase in pumping cost . The higher the cost the more farmers will be affected. These results are shown graphically in Figure 3.3. Figures 3.3a and 3.3b show that a $1 increase in cost of pumping shifts the switching point from 28 to 29.2 acre-inches per day. Under this price change wells below 29.2 acre-inches per day reduce both irrigated acres and irrigation depth, while wells above this well capacity only adjust their irrigation depth. As can be seen in figure 3.3c, the size of the decrease in seasonal water use is the highest among a range of well capacities near the switching point. This finding is important in studying price elasticity of demand. The results suggest that changes in water consumption are not monotonic across well capacities. Well capacities close to the switching point have the largest response to changes in the cost of water because they adjust both on the extensive and intensive margins. This result suggests that when considering water pricing policies, regulators should consider the heterogeneous effects of such policies. We will further explore this in Section 3.4.3. The result also suggests that assuming a homogenous response or a representative farmer may not be a valid assumption when studying price elasticity of demand. Empirical models should control for the range of well capacities.

Finally, Figure 3.3c also suggest that even though the price elasticity of water demand is very small for low well capacities, it is not zero. This is in contrast to the case where total seasonal water availability is a constraint for production. In the case of a seasonal limit, price elasticity of demand will be zero for the constrained portion of well capacities (Wang and Nair, 2013). However, results of this section show that even for very low well capacities price elasticity is not zero analytically.

3.4.2 Effects of a Change in Climate Conditions

Heterogeneity in groundwater availability is also important for studying the effects of climatic changes on irrigated agriculture. Climatic changes could result in changes in seasonal and intra-seasonal water availability in terms of precipitation and surface flows. Recent studies (e.g. Fishman (2011)) show that not only seasonal water availability affects irrigation decisions, intra-seasonal variations are also important for irrigation decisions and profits.

In this model, drier climate conditions affect irrigation revenue through ϵ. In reality, climate has two distinct effects on crop production. First, in a drier climate, expected seasonal water application should be higher to achieve higher expected crop yields. Second, in a drier climate, average daily water availability, particularly during the critical stages of the growing season and in form of average soil moisture, decreases. As a result, in a drier climate, at any level of maximum daily application rate, expected crop yield is lower. This difference becomes smaller for higher maximum daily application rates since the farmer can buffer for dry conditions at the critical stages of the growing season with higher application rates. In general, a drier climate can be thought of as a combination of seasonal and intra-seasonal effects on crop yield.

The results show that the effect of drier conditions (i.e. an increase in

ϵ) on profit-maximizing decisions is complex. Analytical results are shown in Appendix B and graphical results using the numerical analysis of the characteristics of Chase County are shown in Figure 3.4. Based on the results of Section 3.3, we know that a farmer with high well capacity can meet the daily crop water demand during the growing season in dry years by applying more water. Thus, in a drier climate, the farmer applies more water than in the current climate, while they apply less water in a wetter climate. With intermediate and lower well capacities, however, the farmer needs to adjust their irrigated acres to provide higher instantaneous irrigation capacity to be able to meet the higher demand during the critical stages of the growing season in drier climates. Figure 3.4a shows that intensive margin application increases for every well capacity as the climate gets drier. Figure 3.4b shows changes in expected seasonal groundwater application as a function of changes in climatic conditions. We can see that in a drier climate, expected seasonal application is higher for a farmer with high well capacity, while the expected seasonal application is lower for a farmer with low well capacity.

As we can see, the reduction in water consumption is largest for intermediate well capacities near the switching point. These results suggest that the effect of future climatic changes among farmers may be more complex than previously thought. While farmers with higher well capacities can buffer against the drier climatic conditions, farmers with lower capacities may not have the same capability. This issue can be even more significant if aquifer levels keep declining and well capacities further decrease with decline in aquifer levels.

These results also suggest that the effects of changes in climatic conditions are neither homogenous nor linear across farmers with different access to instantaneous groundwater supply. This is in contrast to the studies that do not consider intra-seasonal groundwater availability as a limiting factor for irrigated agriculture (e.g. Tsur (1990)). In these models, any farmer can meet crop water demand in drier climates. Taking into account the effect of well capacity limitations is thus important in understanding the buffer value that an aquifer can provide. Finally, Figure 3.4c shows the effect of changes in climate on profits. The effect of a drier climates on profit is non-monotonic, and it is highest among intermediate well capacities which suggests that farmers with intermediate well capacities may be the most vulnerable, in terms of potential reductions in profits, to future climatic changes.

3.4.3 Welfare Effects of Aquifer Stabilization Policies

An important application of the model developed in this paper is in understanding the cost-effectiveness and welfare effects of different policies that intend to reduce groundwater extraction. With aquifer levels rapidly declining, there is significant demand from farmers and policy makers to reduce groundwater extraction from irrigated agriculture to either stabilize the aquifer in areas with higher recharge or extend the economic life of the aquifer in areas of lower recharge. Most existing policies are uniform across space (Guilfoos et al., 2016) and do not change significantly over time. Existing literature often does not consider heterogeneity among farmers in terms of access to instantaneous groundwater supply in their analysis of different policies. In this section, I study four different policies for reducing groundwater extraction and compare them in terms of cost-effectiveness and their heterogenous distributional effects among farmers.

The focus of this section is on the Upper Republican Natural Resources District (URNRD) in southwest Nebraska. The district is within the Republican River Basin which is one of the most highly regulated areas in the High Plains Aquifer with significant interest among local water managers to protect the Republican River from the impacts of pumping. There are 3333 active agricultural wells between 5.3 and 80 acre-inches per day capacity (100 and 1509 gallons per minute respectively) in the basin. Well capacity data at the time the well were drilled was obtained from the Nebraska Department of Nebraska well database. They were then adjusted to actual well capacities using the equation provided in (Koester, 2004). Figure 3.5 shows the distribution of well capacities in the District. The average well capacity for the URNRD is 47.5 acre-inches per day which is above the switching point of 28 acre-inches per day derived in Section 3.3. The standard deviation of well capacities is 13.14 acre-inches per day. As we can see, there are not many wells below the switching point in the URNRD for current climatic conditions.

We consider four policies to reduce consumption. First, taxing a unit of water, i.e. a pumping tax. Current rules in the URNRD mandate new wells to have an approved flow meter installed on wells. Second, taxing an acre of irrigated land which is called an occupation tax in Nebraska and was set at $10 per irrigated acre in 2007 (Aiken, 2012). Third, limiting irrigated acres homogeneously across farmers assuming a 130 acre irrigated parcel which is the area of a quarter section center-pivot circle. I call this policy "percent irrigated acres". This policy assumes every farmer owning a well can irrigate 130 acres of land and bases the reduction in consumptive use on this assumption. Finally, a policy that reduces irrigated acres based on the currently certified acres of farmers. This policy assumes that the initial number of certified acres is the profit maximizing number of irrigated acres for each farmer. We obtain the profit maximizing quantity of irrigated acres by solving equation 3.1 for each farmer. This policy, although similar to the Conservation Reserve Enhancement Program (CREP) in that it targets irrigated acres, does not intend to retire the entire parcel for some farmers, but rather intends to reduce the same proportion of irrigated acres across all farmers. Since we are interested in cost-effectiveness of these policies (as well as distributional effects), we assume that the amount paid in taxes could be returned to the farmers in some way. In this way, we only compare the policies based on their effect on profits due to reduction in groundwater extraction rather than a combination of changes in productivity and taxes (Hendricks and Peterson, 2012).

Figure 3.6a shows the decrease in profits as a function of a decrease in the level of water consumption for different policies. The decrease in water consumption and profit occurs due to "tighter" policies. We can see that the pumping tax is the cost-effective policy among the four policies proposed. We also note that the ranking of the policies remains the same for different levels of reduction in groundwater extraction suggesting that the pumping tax could provide the highest savings for any level of reduction target given that all pumps are required to install flow meters. Among the three land-based policies, while an acreage tax is the most cost-effective policy, these three policies are very similar in terms of cost-effectiveness. This similarity suggests that the assumption on the number of irrigated acres by policymakers may not have a significant effect on the savings of the policy. Policymakers can assume homogenous irrigated acres across farmers.

Cost-effectiveness is not the only consideration for aquifer management policies, but welfare effects are also important. Guilfoos et al. (2016) mention two main reasons for the importance of distributional effects of different policies. First, policies with a negative effect on many farmers may not be implementable. Second, given that most policies are simplified to be uniform across space and time, it is important to understand their effects on farmers that are located within a heterogenous aquifer. I study this case by adding well capacity as a source of heterogeneity among farmers and look at the distributional effects. Specifically, I look at the distribution of water use and profits for the proposed policies. The results are shown in Figures 3.6b and 3.6c. These two figures show the distribution of water consumption and profit for 20% reduction in extraction from the case of no policy. This reduction is shown with a dashed-line in Figure 3.6a.

In each graph, we can compare the outcomes under different policies with a status-quo with no policy. The results show that different policies affect farmers with different well capacities differently both in terms of water consumption and in terms of profits. From Figure 3.6b, we can see that under an occupation tax, most of the reduction comes from the intermediate and low capacity wells, while the three other policies reduce groundwater extraction mainly from intermediate and high capacity wells. The policy based on the proportion of 130 acres does not affect groundwater extraction for low capacity wells. This makes sense since the farmers have already adjusted their irrigated acres and pump less groundwater as a result. The cost-effective policy, the pumping tax, will also result in reduction in extraction from higher capacity wells. This finding shows that the distribution of reduction in groundwater extraction under taxing policies is different. Under a pumping tax, the reduction in extraction mainly comes from farmers with intermediate and high capacity wells, while under an acreage tax, most of the reduction comes from farmers with intermediate and low capacity wells. From a policy perspective, if there are regions within the aquifer that have lower saturated thickness and as a result lower well capacities, an acreage tax can result in larger reduction in extraction in these areas which can extend the "local" life of the aquifer. This can be particularly important in cases where lateral flow of the aquifer or the recharge rate is slower than the extraction rate, or in the cases where there is significant spatial heterogeneity in aquifer characteristics. Local aquifer levels are important because negative pumping and stock externalities can be important in local low well capacity areas.

The aforementioned results make more sense when we look at Figure 3.6c that shows the distribution of profits. We can see that the reason the pumping tax is the cost-effective policy in this case is because it results in large reductions in water consumption, mainly among farmers with high capacity wells, with relatively small reductions in profit. An acreage tax, on the other hand, results in larger profit reductions among farmers with low capacity wells. The two policies that target reducing number of irrigated acres by imposing limitations on the number of irrigated acres result in large reductions in profit among farmers with high capacity wells but do not significantly affect the profits for farmers with lower capacity wells. This is important for understanding the distributional effects of different policies. From a policy perspective, if low well capacities are a result of local physical aquifer characteristics other than saturated thickness, an acreage tax may put a higher burden on farmers with low well capacities that have lower productivity. On the other hand, if the local low well capacities are due to low aquifer levels, an acreage tax may be the preferred policy.

Changes in water use depicted in Figure 3.6b also provide some insight about the performance of a potential groundwater market. For example, a market with a cap set at 80% of current extraction rates, under the assumption of no transaction costs, will reach the same allocation at the equilibrium as the tax values in Figure 3.6b. Figure 3.6b suggests that for a groundwater market where groundwater rights are defined based on the quantity of water extracted, if the permits are allocated equally among farmers, we expect farmers with high capacity wells to be the buyers and farmers with low capacity wells to be the sellers. On the other hand, if the groundwater permits are defined based on the number of acres irrigated, we expect farmers with high capacity wells and farmers with low capacity wells to be the sellers, and farmers with intermediate well capacity to be the buyers in the market. This information can be very useful in understanding the ex-ante performance of markets. Policymakers should pay attention to the distribution of the wells and the type and distribution of groundwater rights within the district in determining whether a groundwater market can be an appropriate choice.

3.5 Conclusion

In this paper, I studied the effects of instantaneous groundwater availability on irrigation decisions and profit of a profit-maximizing farmer. The existing economics literature assumes an abundant instantaneous supply of groundwater from aquifers. However, agronomic and engineering literatures show that instantaneous groundwater availability is a major factor affecting crop production and it is important to meet crop water demand during the critical stages of the growing season. This paper captures these observations within the decision making framework of a profit-maximizing farmer. The results of the analytical model show that instantaneous groundwater availability does affect irrigation decisions. Specifically, there exists a well capacity (the switching point) below which a profit maximizing farmer will not irrigate their entire parcel, but reduces irrigated acres instead to provide enough capacity to meet crop water demand during the critical stages of the growing season. As a result, water consumption and profits are significantly lower for well capacities below the switching point.

The analytical findings have important policy implications. The results suggest that farmers with well capacities slightly above the switching point are the most affected by water pricing policies because such policies affect their decisions both at the intensive and extensive margins. This suggests that price elasticity of demand for groundwater is non-monotonic across well capacities, where a medium range of well capacities has the highest response to an increase in the price of water. Results suggest that policymakers should consider the distribution of wells when considering a water pricing policy. The results can also have implications for the effect of energy policies on irrigation decisions. I also show that farmers with intermediate well capacities can be the most vulnerable to dry weather conditions, which has important implications for the effect of climate change on irrigated agriculture. Climatic changes are expected to affect both seasonal water availability and the intra-seasonal distribution of rainfall. Results of this study suggest that while drier climatic conditions affect all farmers with different well capacities, the effects, in terms of profit, are most severe among intermediate well capacities. From a policy perspective, we should note that with further extraction from the aquifers, well capacities are expected to decline. In regions currently with many wells with high well capacities, this distribution may shift towards lower well capacities. A larger number of wells with intermediate well capacities could mean larger impacts from future climatic changes.

Furthermore, I find that overlooking the effect of instantaneous groundwater availability on irrigation decisions through its effects on crop yield could result in miscalculating the effectiveness of groundwater policies. Existing models assume a uniform response among different types of farmers and a homogenous demand function. For example Feinerman and Knapp (1983) compare the effect of a pumping tax and an acreage tax on pumpers but do not consider instantaneous groundwater availability as a source of heterogeneity. Results of my study suggest that since it is important to consider both cost-effectiveness and who the policy intends to target to reduce groundwater extraction, policy makers should take into account that farmers with different well capacities respond differently to different policies.

Moreover, efficiency and cost effectiveness is the focus of most groundwater management policies but distributional effects have not received much attention. Equity both within and across generations is an important concern for the public interest (Peterson et al., 2003). The results show that farmers with different well capacities respond differently to different water policies and the effects on their profits are also different. This finding is important in understanding the effect of aquifer management policies across farmers in aquifers with heterogenous physical characteristics. For example Peterson et al. (2003) argue that the bedrock of the High Plains Aquifer is very unequal between farmers. Results of this study suggest that even though a pumping tax is a cost effective policy, an acreage tax could be preferred if maintaining local parts of an aquifer is a priority.

Furthermore, the buffer value of an aquifer is not the focus of this study, Our results suggest that the buffer value of an aquifer against dry weather conditions depends on saturated thickness suggesting that the literature that do not consider instantaneous groundwater availability (Tsur, 1990; Gemma and Tsur, 2007) may provide biased results for buffer value of aquifer, i.e. they may overestimate the buffer value of aquifer when saturated thickness is low and thus underestimating the value of aquifer management when buffer value of aquifer is still high. Future research should study buffer value of the aquifer considering well capacity in more depth.

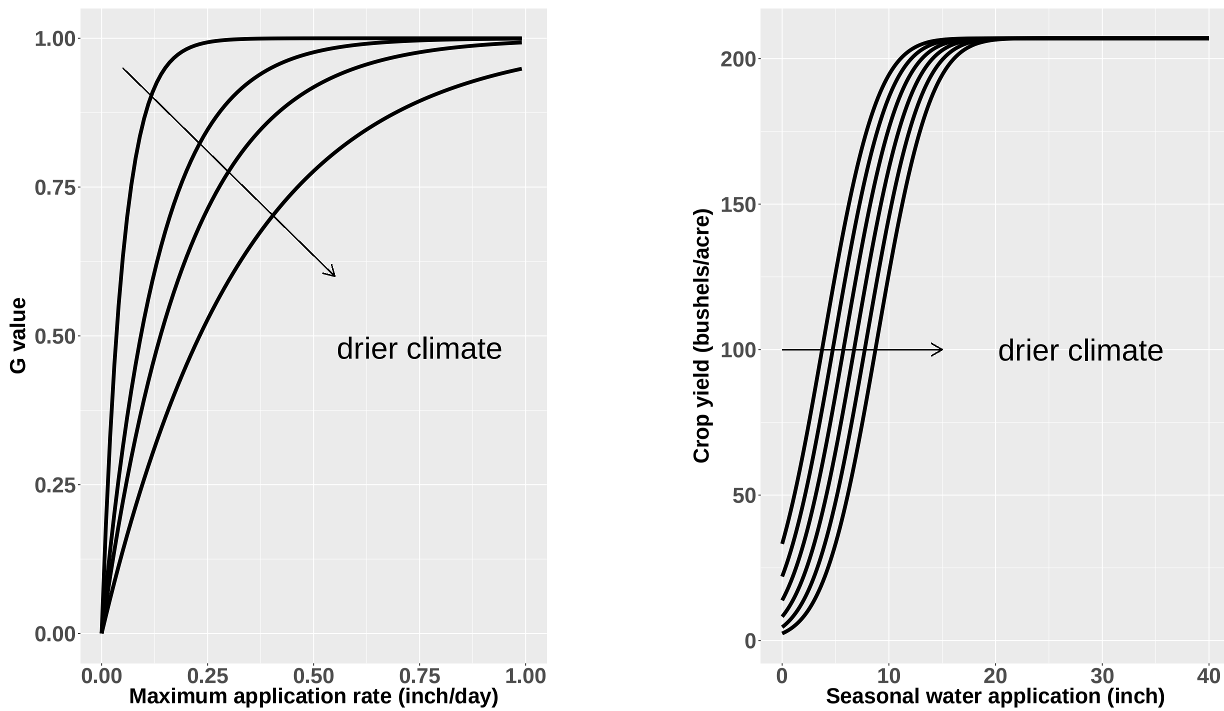
Provencher and Burt (1993) argue that three types of pumping externalities exist: a stock externality which is a reduction in the stock of available groundwater for future pumping, a pumping cost externality which is the increase in cost of pumping due to pumping groundwater, and a risk externality which reduces the buffer value of aquifer against income risk. Our results suggest that there exists a well capacity externality that reduces expected profits of neighboring farmers during the life aquifer by reducing their well capacities. Future research could further investigate these claims using a spatial model and considering the effect of instantaneous groundwater availability on crop yield and the effect of saturated thickness on well capacity.

Finally, even though this study does not include a dynamic model, its results can provide insight into the temporal and spatial benefits of aquifer management. Our results are important for temporal value of aquifer management when we consider that as aquifer levels decline, well capacities also decline (Brookfield, 2016; Hecox et al., 2002). The results suggest that an increase in pumping cost is not the only effect on irrigation decisions, and that the demand function throughout the life of the aquifer will not be the same as assumed in earlier models such as Gisser and Sanchez (1980), but will be nonlinear. Also, the decline in well capacity means that the future distribution of well capacities may not be the same. As a result the distribution of profits within the aquifer management district or basin could change over time. Future research could study the changes in distribution of well capacities on the effectiveness of aquifer management policies using dynamic models.

3.6 Tables and Figures

Table 3.1: Parameter values used in profit maximization

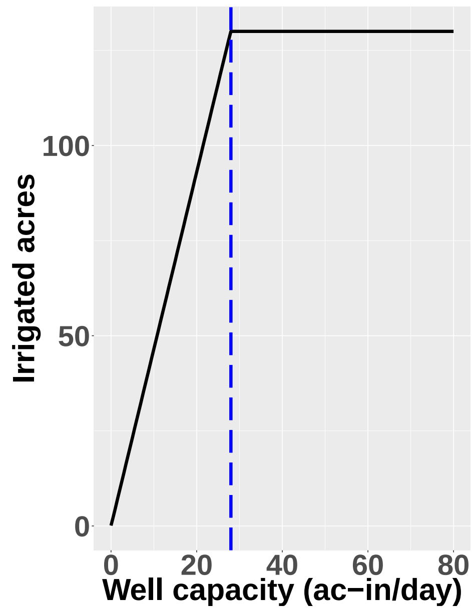
parameter	Value
Price of corn per bushel ($)	4.15
Cost of pumping a gallon of groundwater ($)	2.17
Maximum attainable corn yield (bushels)	219.2
Fixed costs ($ per acre)	400



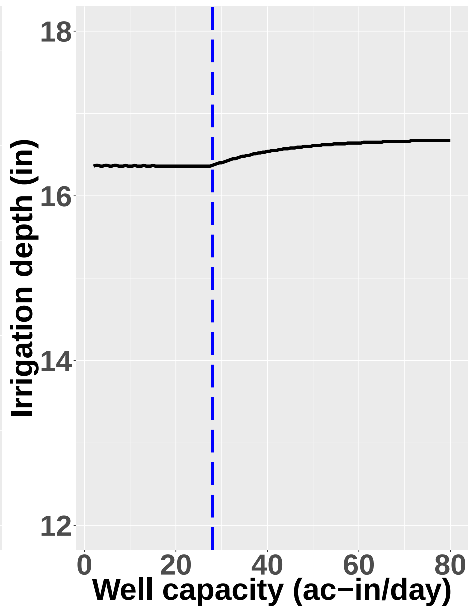
(a) G function

(b) Φ function

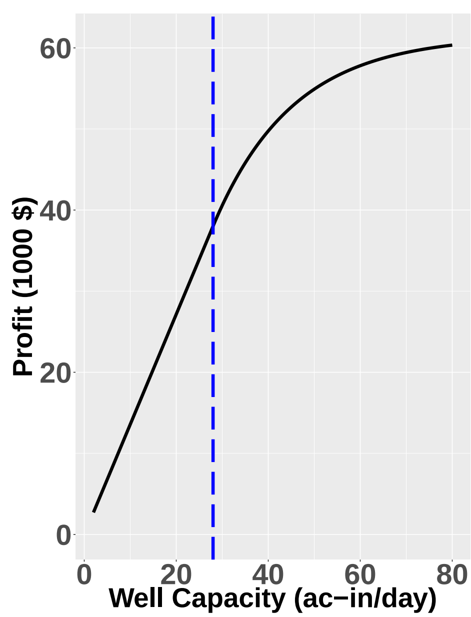
Figure 3.1: Elements of crop production function and the effect of changes in climatic conditions on crop yield. a) shows $G(\frac{X}{A}, \epsilon)$ which captures the effect of daily water availability on crop yield. b) $\Phi(u, \mu + \epsilon, \sigma)$ which is the effect of intra-seasonal water application on crop yield.



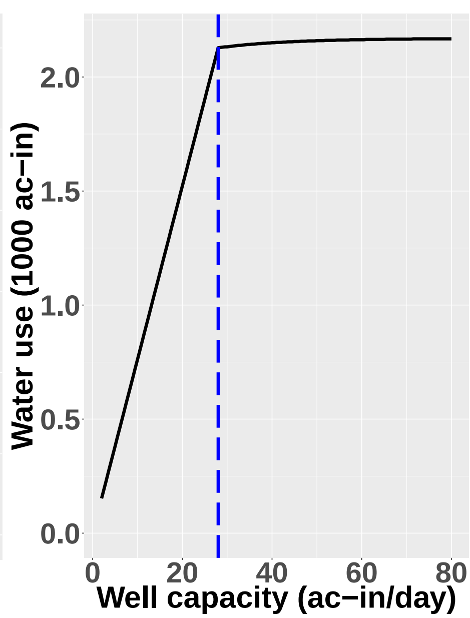
(a) Profit-maximizing portion of acres irrigated



(b) Profit-maximizing irrigation depth

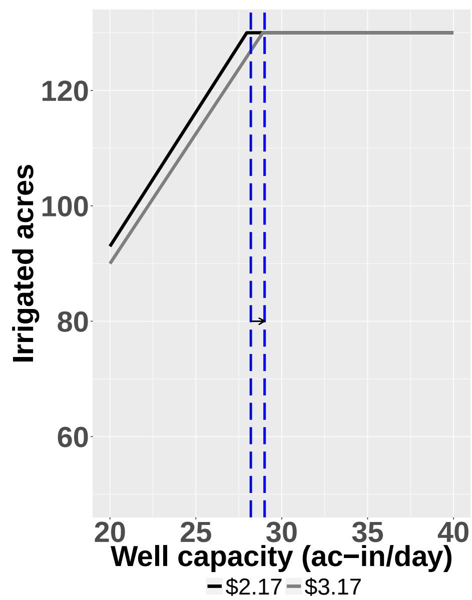


(c) Maximum profit

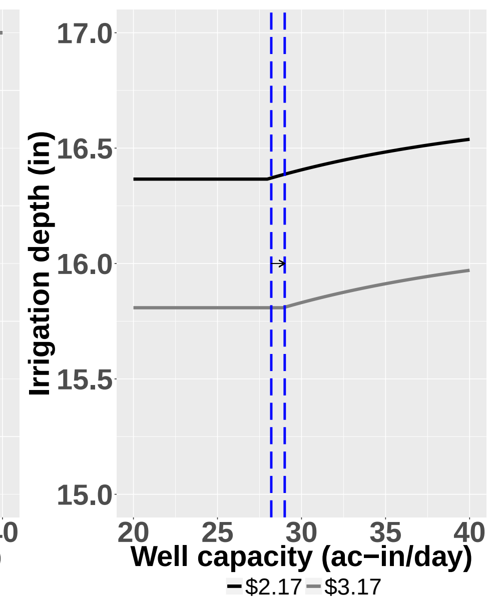


(d) Expected seasonal water use

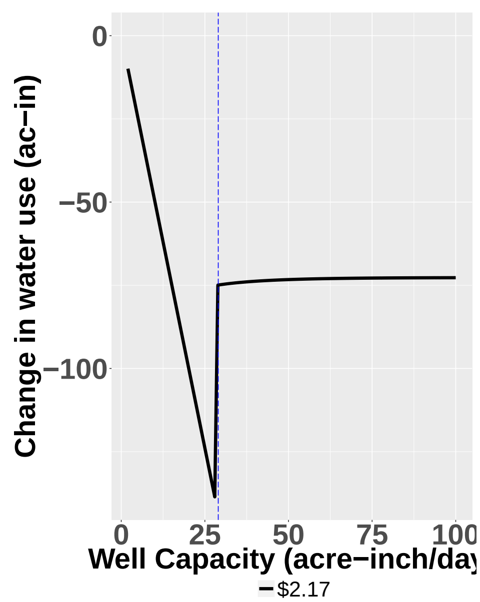
Figure 3.2: Profit-maximizing levels of a) irrigated acres b) irrigation depth, c) maximum profits, and d) seasonal water use under different levels of instantaneous groundwater availability (well capacity). The dashed-line shows the switching point above which the decision is to adjust irrigation depth and below which the profit-maximizing decision is to adjust the number of acres irrigated.



(a) Effect of pumping cost on irrigated acres

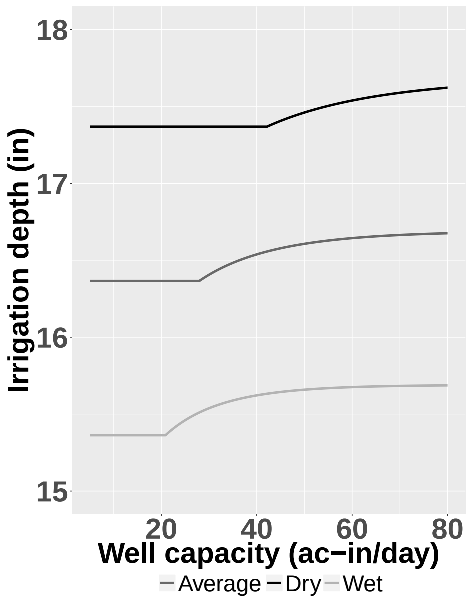


(b) Effect of pumping cost on irrigation depth

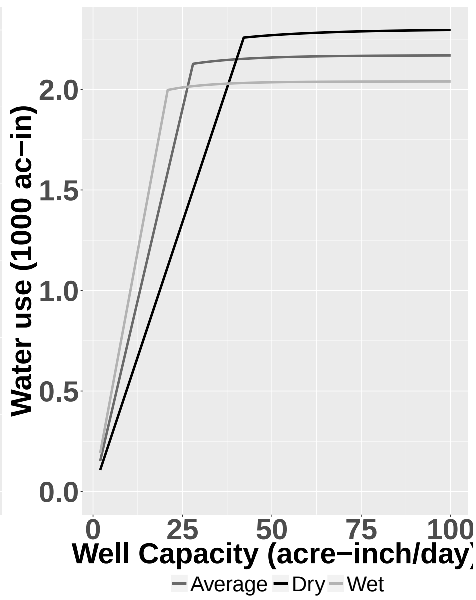


(c) Effect of a $1 increase in pumping cost on seasonal water consumption

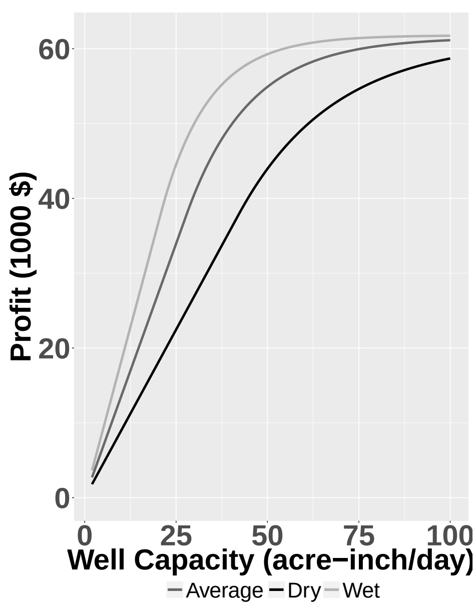
Figure 3.3: Figures a) and b) show irrigation depth and seasonal water application for a 130-acre field as a function of well capacity for different pumping costs. As pumping cost increases, both irrigation depth and total water application decrease, while the switching point shifts to the right. Panel c) shows the effect of a $1 increase in cost of pumping on water application at $2.17 and $3.17. We can see that the effect is non-monotonic.



(a) Effects of climatic conditions on irrigation depth



(b) Effects of climatic conditions on seasonal water application



(c) Effects of climatic conditions on profit

Figure 3.4: Effects of changes in climate, ϵ, on a) irrigation depth, b) seasonal water use, and c) profit. As ϵ increases, the switching point shifts to the right. We can also see a non-monotonic change in seasonal water use and profit from an increase in ϵ.

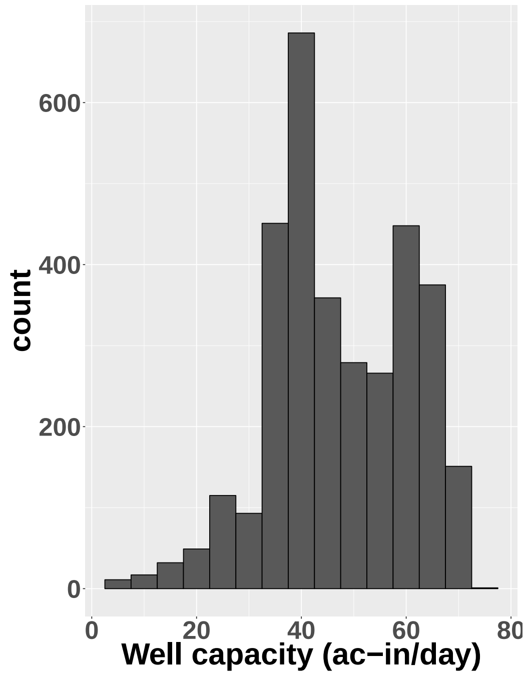
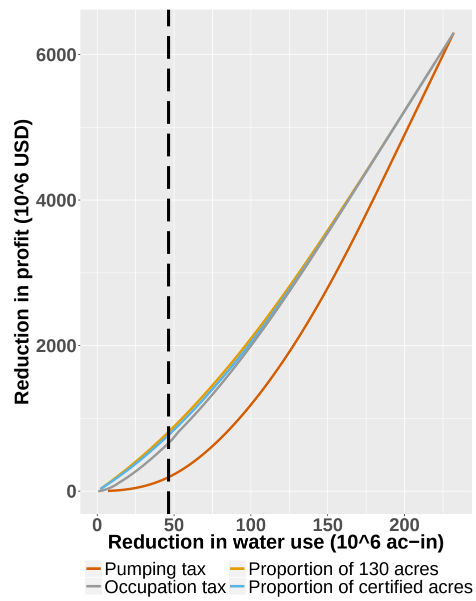
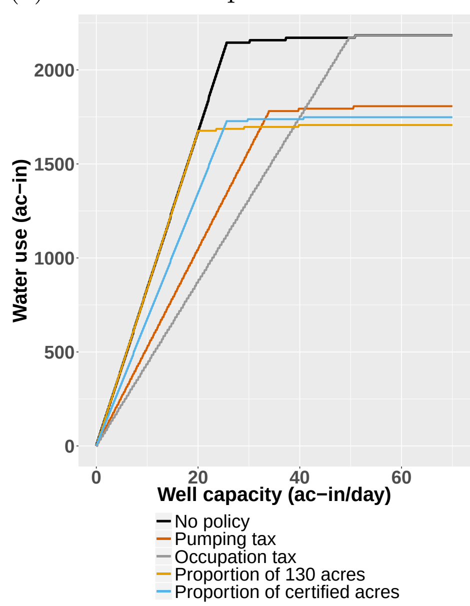


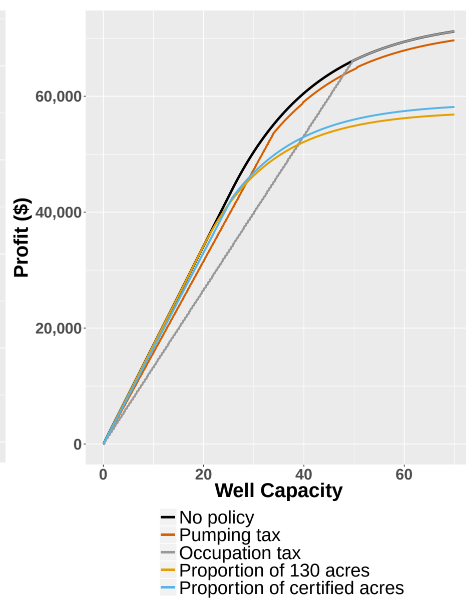
Figure 3.5: Histogram of well capacities in the Upper Republican Natural Resources District, Nebraska



(a) Reduction in profit as a function of a reduction in water use in the study area



(b) Water use across farmers with different well capacities



(c) Profit across farmers with different well capacities

Figure 3.6: Panel a) shows the loss of profit as a result of reducing water use for each policy. Panels b) and c) show changes in water use and profit for profit-maximizing farmers with different well capacities for each policy set to reduce total extraction in the District by 20%.

CHAPTER 4

LOSS OF BUFFER VALUE DUE TO AQUIFER DEPLETION: THE CASE OF THE NORTHERN HIGH PLAINS AQUIFER

4.1 Introduction

Aquifers serve both as a source of water supply to increase crop yield and to buffer against the variability of precipitation and surface water flows during a crop growing season. Most existing studies have focused on the former, while the role of an aquifer in buffering against the variations of weather during a growing season is significantly understudied within the economics literature. In the third chapter of this dissertation, I showed that groundwater availability during the growing season can significantly affect irrigation decisions and profits of agricultural production. In this chapter, I build on the framework developed in chapter 3 to study the loss of buffer value of aquifer due to aquifer depletion. I then apply the methodology to the case study of the northern portion of the High Plains Aquifer which includes parts of Nebraska and Kansas to estimate the loss of buffer value between 1980 and 2009.

Groundwater has been a major factor in increasing agricultural production over the past decades. Increasing extraction rates that exceed natural recharge rates have resulted in significant declines in aquifer levels raising concerns about vulnerability of agricultural production to dry weather conditions and droughts. While there is recent evidence on the increasing risks of agricultural production in the past few years, existing studies have explained it as a result of changes in management practices such as increasing density of planted crops (Lobell et al., 2014), and an increase in the number of irrigated acres and switching to water intensive crops (Hornbeck and Keskin, 2014). These studies, however, do not consider the role of aquifer depletion in increasing variation in crop yields. This is specially important because under most existing explanations about the role of aquifers, existence of an aquifer is sufficient for buffering against dry weather conditions.

Recent studies, however, show that instantaneous groundwater availability during the growing season matters for farmers' irrigation decisions (Foster et al., 2014) and for their ability to buffer against drought (Foster et al., 2015b).

Many of the existing economic studies consider increases in costs of pumping as the channel through which changes in aquifer levels affect irrigation profits (Gisser and Sanchez, 1980; Provencher and Burt, 1994; Knapp and Olson, 1995). Others consider the case of catastrophic events, such as saltwater intrusion as another cost to aquifer depletion. These studies mainly focus on optimal management of groundwater aquifers under event uncertainty (Tsur and Zemel, 1995, 2004). In this paper, we explain another channel, namely loss of buffer value, as a channel through which aquifer depletion can affect irrigated agriculture.

There has been several economic papers, by Yacov Tsur and his colleagues, that studied the buffer value of aquifers (Tsur, 1990; Tsur and Graham-Tomasi, 1991; Gemma and Tsur, 2007) under static and dynamic settings. In these studies, Tsur and his colleagues find a positive buffer value for groundwater. However, they consider changes in depth to water as the only mechanism through which aquifer depletion affects irrigation decisions. They implicitly assume that at any saturated thickness water is available in unlimited quantities which suggests that a farmer can buffer against dry weather conditions as long as the marginal cost of pumping is not too high. As a result of their assumption, production risk translates into cost of pumping meaning that aquifer depletion results only in higher pumping costs to buffer against dry weather conditions.

In Chapter 3, I developed a framework that explicitly takes into account the effects of pumping rates on a profit-maximizing farmer's irrigation decisions about the number of irrigated acres and application rates per acre. The results in chapter 3 suggest that aquifer depletion not only affect cost of pumping, but it can directly affect crop yield. In this chapter, I build on the model developed in chapter 3 and develop a framework to study the loss of buffer value of an aquifer. I apply the methodology to estimate the loss of buffer value within a portion of the High Plains Aquifer consisting of 3 counties in Nebraska and 2 counties in Kansas between 1980 and 2009.

The High Plains Aquifer is one of the major aquifers in the United States, underlying portions of eight states. The aquifer is an important source of water supply for agricultural production, accounting for more than 30% of groundwater withdrawals from aquifers in the US. It is also an important source for agricultural-dependent economic activities for the region. Recent studies have shown a significant decline in groundwater levels in portions of the aquifer from pre-development levels (McGuire, 2014). Since these declines in aquifer levels could result in changes in the capacity at which farmers can extract groundwater (Hecox et al., 2002), they could have significant implications for agricultural production risk.

The importance of the High Plains Aquifer and rapid rates of depletion have attracted much attention from policy makers and the scientific community about the consequences of the existing extraction rates. Several recent studies have analyzed changes in levels and storage of the High Plains Aquifer mainly focusing on the the lifespan of the aquifer based on existing extraction rates (Steward et al., 2013; Scanlon et al., 2012; Tidwell et al., 2016). These studies suggest that changes in the storage of the High Plains Aquifer are very localized and are heterogenous. However, these studies do not explicitly take into account the effects of aquifer depletion on irrigation decisions and profits, and while they mention that aquifer depletion has resulted in lower well capacities, they do not take these changes into account. Thus, existing studies provide limited insights into the benefits of aquifer management.

In this chapter, I study the loss of buffer value due to aquifer depletion in Chase, Dundy, and Perkins counties in Nebraska, and Cheyenne and Sherman counties in Kansas. I find that there is significant variability in the effects of aquifer depletion on the buffer value of the aquifer within the study area. While most of the study area has experienced losses estimated at less than $30 per acre between 1980 and 2009, some parts have experienced losses of up to $100 per acre. Furthermore, I find that the effect is more significant in the southern part of Nebraska and the Kansas portion of the study area. Finally, I find that initial saturated thickness, as well as aquifer depletion are important determinants of the loss of buffer value.

4.2 Methodology

Engineering studies suggest that as aquifer levels decline, the instantaneous supply of groundwater from an aquifer decreases (Theis, 1935). The decrease in instantaneous groundwater supply is nonlinear such that for high saturated thickness levels, changes in aquifer level result in small changes in the instantaneous supply of groundwater. However, at lower saturated thickness levels, similar changes in aquifer level can result in much larger reductions in the instantaneous supply of groundwater from an aquifer. Agronomic studies, on the other hand, suggest that the instantaneous supply of water during the growing season is critical for crop growth (Rogers et al., 2015; Schneekloth et al., 2009; Martin et al., 1984; O'Brien et al., 2001; Lamm, 2004; Lamm et al., 2007). Together these literatures suggest that there may be consequences to aquifer depletion beyond an increase in pumping cost that have been ignored within the economics literature and in policy making.

In Chapter 3, I developed a production function, $G(\frac{X}{A})(M)\Phi(u, \mu, \sigma)$, that captures both the inter-seasonal and the intra-seasonal nature of irrigation demand and decisions. The inter-seasonal part of the production function, $\Phi(u, \mu, \sigma)$, explains the effect of instantaneous groundwater application on crop yield under current climatic conditions taking into account crop, soil and technology characteristics. This function is a cumulative distribution function and provides a solution to the intra-seasonal decisions of a farmer under stochastic conditions when there are no limitations on instantaneous groundwater supply.

The inter-seasonal part of the production function, $G(\frac{X}{A})$, takes into account the effect of well capacity, X, on crop yield through maximum instantaneous application rate, $(\frac{X}{A})$, where A is the number of irrigated acres. The maximum instantaneous application rate is the maximum amount that can be applied to an acre instantaneously. In practice, this ratio is a proxy for how well an irrigation system can keep up with soil moisture deficits during the growing season. The ratio is also a practical value that is used in many design and irrigation guidelines which makes it a relevant factor within an irrigation decision framework. The G function suggests that a farmer's ability to keep up with soil moisture demand for crop growth during the growing season depends on maximum application rate per acre which itself depends on instantaneous amount that can be extracted from the aquifer and the number of irrigated acres. Since this function captures the effect of allocated irrigated acres in crop yield, it captures the inter-seasonal nature of irrigation decisions. G is increasing and concave in $(\frac{X}{A})$ suggesting that keeping the number of irrigated acres fixed, as the amount of groundwater that can be extracted from the aquifer, X, decreases, a farmer's ability to meet crop water demand during the critical stages of the growing season decreases at an increasing rate.

In Chapter 3, I used this production function in a framework of a profit-maximizing farmer to determine the share of irrigated acres, extensive margin, groundwater application per acre, intensive margin, and irrigated profits for a given climate. The results in the previous chapter showed that a decrease in well capacity could affect irrigation decisions and profit nonlinearly. In this chapter, I build on the framework introduced in Chapter 3 and add nonlinearities in the effects of aquifer depletion on instantaneous supply of groundwater to study the effects of aquifer depletion on loss of buffer value for irrigated agriculture. In this framework, a risk-neutral farmer maximizes their expected profit based on groundwater availability, crop, technology and biophysical characteristics:

$$\begin{aligned} \underset{A,u}{\text{Max}} \quad & A\left\{PG(\frac{X}{A},\epsilon)(M)\Phi(u,\mu+\epsilon,\sigma)-\Gamma(Y)u\right\} \\ \text{subject to} \quad & A \leq 1 \\ & A, u \geq 0 \end{aligned} \tag{4.1}$$

In equation 4.1, A, number of irrigated acres, and u, expected application rate per acre, are the decisions variables and while they are determined simultaneously in the model, the model captures the two-stage nature of the decisions. P is the price of the crop, X is well capacity, and μ and σ are parameters of the production function. Y is saturated thickness, and $\Gamma(Y)$ is the marginal cost of pumping groundwater. M is the maximum attainable yield. $G(\frac{X}{A})\Phi(u,\mu,\sigma)$ is expected crop yield per acre.

Instantaneous supply of groundwater is a function of saturated thickness, which is the saturated portion of the aquifer and is measured as the height of the groundwater level from the base of the aquifer, as well as physical aquifer characteristics such as specific yield, which is a measure of the ability of an aquifer to supply groundwater as a result of pumping. Specifically, changes in saturated thickness affect instantaneous supply of groundwater nonlinearly such that $\frac{dX}{dY} > 0$ and $\frac{d^2X}{dY^2} < 0$. These changes directly enter into the farmer's decision making and affect irrigation profit. I define the change in the buffer value of the aquifer from year t to year $t - \kappa$ as the change in the (maximized) expected profit due to the change in the capacity of the aquifer to supply groundwater keeping irrigation cost, prices and climatic conditions fixed:

$$\begin{aligned}&\textit{Annual change in buffer value between } t \textit{ and } t-\kappa = \\ &\qquad (\textit{Expected profit}|P_t, \Gamma(Y)_t, \epsilon_t)_t - (\textit{Expected profit}|P_t, \Gamma(Y)_t, \epsilon_t)_{t-\kappa}\end{aligned} \tag{4.2}$$

This definition is different from that of Tsur and Graham-Tomasi (1991) and an often commonly understood concept of buffer value in economics which focuses on risk aversion. In the definition used in this chapter, buffer value refers to the ability of a (risk-neutral) farmer to meet the intra-seasonal demand of a crop during the growing season based on the instantaneous supply and availability of groundwater. In Tsur and Graham-Tomasi (1991), changes in buffer value become translated into pumping cost. However, in the model in this chapter, changes in buffer value directly affects expected crop yield. This definition captures biophysical characteristics of groundwater supply and the intra-seasonal nature of irrigation decision making based on stochastic weather conditions. The framework does not intend to compare the difference between deterministic and stochastic settings; rather it intends to introduce a more intuitive definition regarding the effect of aquifer depletion on irrigation decisions of a farmer and their ability to "buffer" against the intra-seasonal variability of weather. Furthermore, while risk aversion can be added to this framework, it is not necessary to do so. This is because changes in aquifer level can also affect the intra-seasonal availability of groundwater and expected profits for a risk-neutral farmer. In the next section, I apply this methodology to the case of 5 counties in Nebraska and Kansas overlying the northern High Plains aquifer.

4.3 Case Study

4.3.1 Background

The High Plains Aquifer, sometimes called the Ogallala Aquifer, is one of the largest aquifers in the world, underlying portions of eight states including South Dakota, Wyoming, Nebraska, Colorado, Kansas, Oklahoma, New Mexico and Texas. Among these states, Nebraska, Kansas and Texas overlie the largest area compared to others.

After the Dust Bowl of the 1930s and World War II, the introduction of pumps and center pivot irrigation technologies has significantly increased the share of irrigated agriculture and has changed the economy of the region. Since then the aquifer has been a major support for the agricultural economy of the states overlying the High Plains aquifer, making them the breadbasket of America. Irrigation within the region further intensified during 1980s. Currently, the aquifer provides more than 30% of groundwater withdrawals from aquifers in the US (Tidwell et al., 2016).

The intensification of irrigated agriculture, however, resulted in a significant decline in groundwater levels from pre-development levels in portions of the aquifer (McGuire, 2014). Since these declines in aquifer levels could result in declines in the capacity at which farmers can extract groundwater (Hecox et al., 2002), they could have significant implications for agricultural production risk. Such effects could specially be important under climatic changes (Foster et al., 2015b). While the number of irrigated acres and average irrigated and non-irrigated crop yields have all increased over time, so has the variance of crop yield, despite advances in crop and irrigation technology. As a result farmers have engaged in adaptive behaviors such as reducing irrigated acres to lower production risk (Steward et al., 2013). These findings raise questions about the impact of depletion of the High Plains aquifer on agricultural production risk, food security and local economies of the region.

A notable point about the High Plains Aquifer is that there is significant heterogeneity within the aquifer both in terms of aquifer characteristics, rainfall and recharge rate (Scanlon et al., 2012; Peterson et al., 2003). This heterogeneity has resulted in different demand for groundwater across the regions of the aquifer, and has resulted in different changes in aquifer levels and heterogenous effects on irrigated agriculture. Ignoring this heterogeneity within the High Plains Aquifer can result in biased estimates of the effects of aquifer depletion on irrigated agriculture.

The northern part of the High Plains Aquifer includes South Dakota, Nebraska, Wyoming, Colorado, and Kansas. In this paper, I focus on loss of buffer value in the parts of the aquifer that overlie 3 counties in Nebraska, namely Chase, Dundy and Perkins, and 2 counties in Kansas, namely Cheyenne and Sherman. These counties are located in southwest Nebraska and Northwest Kansas (figure 4.1). While this part of the aquifer has experienced moderate declines in aquifer levels compared to the southern part of the High Plains aquifer, it is important to study loss of buffer value in this are because the 3 counties in Nebraska are among the counties that have experienced the most significant changes in aquifer levels since predevelopment compared to other counties in Nebraska. Furthermore, comparing the loss of buffer value across Nebraska and Kansas can provide some insight into differential changes in buffer values of the aquifer across states.

4.3.2 Data

Well level data for irrigation wells are obtained from two different sources. To obtain well level data for Nebraska, I used Nebraska well database from the Nebraska Department of Natural Resources[1]. I collected well level data for the state of Kansas from the water well completion records (WWC5) database of the Kansas Geological Survey[2]. Both of the datasets include well depth, depth to water and pump rate estimates from pumping tests carried out by the drilling companies and reported in the "drillers log". Each individual needs to submit results of their pumping test when they register their wells to the respective agency in their state.

To estimate saturated thickness of the aquifer in 1980 and 2009, I used the results of the study by McGuire et al. (2012). They provide raster maps of saturated thickness for the entire High Plains aquifer for 2009 and raster maps of changes in aquifer level from 2005 to 2009, from 2000 to to 2005, from 1995 to 2000, and from 1980 to 1995. I combined all these maps to attain saturated thickness in 1980. I further use groundwater level data from the High Plains Aquifer Water-Level Monitoring Study of the US Geological

[1]http://dnr.nebraska.gov/groundwater-data
[2]http://www.kgs.ku.edu/Magellan/WaterWell/

Survey[3]. This dataset includes time series of static water levels at monitoring well stations across the High Plains Aquifer. The observations are collected after the growing season when the groundwater levels are stabilized. This dataset is used to estimate total depth of the aquifer and saturated thickness at different years.

McGuire et al. (2012) also provide a map of specific yield for the northern High Plains Aquifer. I use the data in this map to help determine the effect of saturated thickness on capacity of irrigation wells. Finally, I use county level data on agricultural production from the National Agricultural Statistics Survey of the US Department of Agriculture[4] in order to calibrate the production function for each county. This dataset includes an estimated irrigated yield for each county in each year. The calibration method is explained in the next section.

4.3.3 Effect of Changes in Saturated Thickness on Well Capacity

In order to estimate changes in buffer value between 1980 and 2009, the effect of changes in saturated thickness on well capacity is first estimated. This way, we can explicitly account for changes in well capacity as a result of aquifer depletion over time. To find this relationship, I take advantage of the well level data for irrigation wells at the time the wells were constructed. Individuals are required to submit the results of their well tests at the time of registration. The information submitted includes depth to water table and pump rate of the well. Since this information is submitted at the time of construction, it is exogenous to the farmer's decisions and only reflects the relationship between aquifer characteristics. Since this is a physical relationship and should not depend on a specific location, I use well level records between 1995 and 2016 in Nebraska and Kansas to estimate the relationship.

We are interested in the relationship between well capacity and saturated thickness. The data submitted by individuals, however, does not include saturated thickness and only includes depth to water table. Thus saturated thickness for each irrigation well is estimated through several steps. First, using saturated thickness data available for 2009 and depth to water reported

[3]http://ne.water.usgs.gov/ogw/hpwlms/data.html
[4]https://quickstats.nass.usda.gov/

for USGS monitoring wells, I estimate the depth of base of the aquifer from the land surface using the following simple formula:

$$\text{depth of bedrock from surface} = \text{depth to water table} + \text{saturated thickness}. \tag{4.3}$$

This relationship provides us with depth to bedrock at the location of every monitoring well. Next, by matching each irrigation well with the closest monitoring well, total depth for each irrigation well is estimated. Here, the assumption is that depth of bedrock is the same for the irrigation well[5]. Finally, saturated thickness is estimated by subtracting depth to water table for irrigation wells from their total depth.

The relationship between saturated thickness and well capacity also depends on physical aquifer characteristics such as specific yield. Specific yield is a measure of how much water can be extracted from an aquifer with a unit decline in water table. Thus, we also use specific yield as an independent variable for determining the relationship between pump rate and saturated thickness for each irrigation well. Furthermore, changes in well construction technology and pumping test methods and technology over time can affect the relationship between saturated thickness and well capacity. To control for these changes over time, we use time dummies in the regression. Finally, it is important to notice that the relationship between well capacity and saturated thickness is nonlinear as shown by Hecox et al. (2002). In order to capture this nonlinear relationship, I use the log-form of saturated thickness in the regression. The log form can capture that changes in saturated thickness can have differential effects on well capacity depending on the aquifer level.

The results of the regression are presented in table 4.2. As we can see, the relationship between saturated thickness and well capacity is nonlinear, such that a one percent decrease in saturated thickness results in a reduction of about 75 gallons per minute in well capacity. Furthermore, the coefficient on specific yield follows our expectations so that with higher specific yields, well capacity is higher.

[5]We drop irrigation wells that do not have a monitoring well within a12 mile radius.

4.3.4 Changes in Buffer Value

Figure 4.2 shows saturated thicknesses of the aquifer for the study area in 1980, 2009 and the change in saturated thickness between these two years. Declines in aquifer levels are between 0 and 40 feet. Most of the changes in aquifer levels have taken place in portions of the aquifer with higher saturated thickness where we might expect smaller reductions in the buffer value of aquifer.

Using the regression results presented in Table 4.2, well capacity for saturated thickness at the levels of 1980 and 2009 for each point (pixel) in the 5 counties of the case study is predicted[6]. Figure 4.3 shows the changes in well capacity as a result of changes in saturated thickness between 1980 and 2009. As we can see, most of the study area has experienced declines in well capacity in the region of 110 to 130 gallons per minute, while some regions within the study area have experienced larger declines.

In order to estimate the changes in buffer value, the production function was calibrated for each county by adjusting M in equation 4.1. To do this, I developed a ratio for each county based on maximum crop yield reported in the NASS dataset between 1980 and 2015, compared to that of Chase County. Table 4.1 shows the distribution of the ratio across counties. Maximum attainable crop yield for each county was then estimated by multiplying this ratio by 219 bushels per acre, which is the maximum attainable crop yield in Chase County in Nebraska. Since study counties are along the same latitude, it is assumed that evapotranspiration rates and thus demand for water is the same within the study area. Furthermore, as we can see from Table 4.1, the maximum attainable yields are very close, which can suggest similar production conditions and characteristics among the counties.

Furthermore, well capacities provided as a result of pumping test do not estimate actual pumping capacities during the growing season. This is because the duration of pumping tests is much smaller than actual pumping during the growing season. Thus, well capacities were adjusted using the method provided by Koester (2004) to reflect the actual pumping rates during the growing season rather than initially reported well capacity from the pumping test.

Finally, maximum expected profits were estimated for each point of the

[6] There is a total of 55,000 pixels on the map.

study area using calibrated production functions (equation 4.1), predicted well capacities, weather distribution and corn prices of \$4.15 for 1980 and 2009 keeping everything other than well capacity fixed. A hypothetical 130-acre parcel, which is the area of a quarter-section center pivot system, is assumed at each point to estimate the expected profit for each year. I then subtract maximum expected profits of 1980 from those of 2009 and divide the value by 130 to estimate the loss of buffer value per acre and per year for each point in the study area.

4.4 Results

The results are provided in Figure 4.4 as the annual change in the expected profits per acre for a 130-acre farm in 2009 dollars. These changes are only due to changes in instantaneous groundwater availability keeping the distribution of weather, prices and depth to water fixed for 1980 and 2009 scenarios. This way, I can compare the conditions of 2009 to the counterfactual world where well capacities were maintained at the levels of 1980.

The results show that the Nebraska portion of the study area has experienced moderate changes in buffer value per acre, while the two counties in Kansas have experienced larger decreases in their buffer value. The average annual change in buffer value of the Nebraska portion of the study area has been \$25 per acre. The highest decrease in buffer value is estimated to be \$57 per acre. While average annual decline in the Kansas portion of the aquifer is estimated to be around \$31 per acre, some portions of Sherman County have experienced losses of up to \$100 per acre. To put these estimates in perspective, assuming a corn production of 170 bushels per acre, revenue from an acre of corn is estimated to be \$680 per acre. Furthermore, Table 4.3 provides the estimated annual loss of buffer value for each county along with the rental value of irrigated land. We can see that Chase County has experienced a 15% reduction in buffer value per acre, while Cheyenne County has experienced a 30% reduction in buffer value per acre due to aquifer depletion. The total annual loss of buffer value for the study area as a result of aquifer depletion between 1980 and 2009 is estimated to be around \$10.6 million in 2009 if the aquifer levels were maintained at the levels of 1980.

In order to understand the importance of these results, we can compare them to the effects of changes in the cost of pumping on irrigation profit per acre. Based on the assumptions of 50 feet of irrigation depth, 40 psi pressure at the pump, using a center pivot system, and a price of $1.66 per gallon of diesel, the cost of applying an acre-inch of groundwater is estimated to be $2.17. Maximum changes in aquifer levels for the study area are found to be 40 feet (Figure 4.2). With the same assumptions, the cost of applying an acre-inch of groundwater at the depth of 90 feet is estimated to be $2.77. Assuming that changes in the cost of pumping does not significantly affect irrigation decisions, the increase in cost of applying 16 inches of groundwater per acre is $9.6. This estimate is the effect of changes in aquifer levels on expected profit through their effect on pumping cost. Compared to the range of changes in expected profit due to changes in instantaneous supply of groundwater ($20 to $100), this value shows a much smaller effect as a result of aquifer depletion. The effect from increase in pumping cost is 50% smaller than those from decrease in instantaneous supply of groundwater when aquifer levels are high. At lower aquifer levels, the effect is an order of magnitude lower. This finding specifically highlights the importance of considering the changes in instantaneous supply of groundwater at lower saturated thicknesses.

When studying changes in buffer value, it is important to consider that declines in well capacity can result from aquifer depletion, or low initial saturated thickness levels. The latter is especially important due to the nonlinear nature of the relationship between saturated thickness and well capacity such that at lower saturated thicknesses, a one foot change in saturated thickness can result in a much larger effect in well capacity than at higher saturated thicknesses. Furthermore, it is important to notice that profit will significantly decrease for an expected profit-maximizing farmer as a result of a one unit decline in well capacity when well capacity is low (figure 3.2). Comparing Figures 4.2 and 4.4 we can see this point. These figures show that the most significant changes have taken place at the border of Nebraska and Kansas where there has not been significant reduction in aquifer levels and the decline in buffer value of the aquifer is a result of lower initial saturated thickness levels. Lower initial saturated thickness could be the result of aquifer depletion pre-1980, or of less availability of groundwater in the region due to local physical aquifer characteristics. We can also see from Figures 4.2 and 4.4 that in the southwestern part of the study area, the reduction in buffer value of the aquifer has resulted from both low saturated thickness levels and significant aquifer depletion.

Scanlon et al. (2012) show that changes in aquifer storage is very localized within the High Plains Aquifer. We further show that changes in buffer value of the aquifer are also very localized so that we observe significant differences in change of buffer value even within a county. The results of this study, however, show a stark contrast to studies that merely focus on changes in aquifer levels such as Scanlon et al. (2012). This difference is due to the fact that changes in buffer value of the aquifer are a function of initial saturated thickness and changes in saturated thickness over time. We show that changes in well capacity are not a linear function of saturated thickness. Also, well capacity changes differently with different underlying aquifer characteristics (in this case, specific yield) as saturated thickness changes. Furthermore, there is more to production risk than changes in well capacity. The same amount of reduction in well capacity in two different counties may result in different changes in production risk due to differences in production function. I have captured the effects of differences in county characteristics on production in a production function that is calibrated to long run crop yields in each county. Considering all these factors, we find that changes in buffer value need not necessarily align well with changes in aquifer levels.

4.5 Discussion

When studying the effects of aquifer depletion and the role of aquifer management, it is critical to understand the type of services and functions an aquifer provides. These services depend on the nature of the activity, how income depends on the aquifer, and how it is affected by changes in aquifer levels. Most existing studies have focused on the seasonal benefits of aquifers for irrigated agriculture (Gisser and Sanchez, 1980; Provencher and Burt, 1994; Knapp and Olson, 1995), or the lifespan of the aquifer (Scanlon et al., 2012; Steward et al., 2013) assuming that existence of the aquifer is enough for providing protection against changes in weather conditions. These studies ignore the stylized facts regarding the effects of aquifer depletion on the capacity of the aquifer to provide instantaneous groundwater supply to buffer against dry weather conditions during the critical stages of the season, and thus may provide results that are of little relevance to policy. Since one of the main roles of a groundwater aquifer is to provide a reliable source of supply to supplement scarce precipitation during a growing season and to insure against dry weather conditions, it is important to understand the effect of aquifer depletion on production risk for irrigated agriculture.

This chapter contributes to the existing literature in understanding the effects of declining aquifer levels on irrigated agriculture. Our results suggest that focusing on changes in saturated thickness does not provide the full picture. We need to take into account the channels through which aquifer depletion affects irrigated agriculture both for understanding the effects of previous aquifer depletion and effects future extraction rates. Taking production risk into account can be specifically important for understanding the response of farmers to future declines in aquifer levels and for providing effective policy recommendations.

There is a strong consensus among economists that at current prices, there is little response from farmers to changes in aquifer levels from increasing pumping costs. Results of this study suggest that focusing solely on the costs of pumping may significantly underestimate the negative effects of aquifer depletion. Increasing production risk is a major effect that has been widely understudied by economists and deserves more attention. Furthermore, a widely held belief among many economists is that irrigation can offset the impacts of weather variations. However, the ability of the aquifer to buffer for these variations is limited and as aquifer levels decline, this ability may further decrease. A decline in the instantaneous supply of groundwater could result in significant increases in production risk.

This study can also contribute to the literature in understand the value of natural capital by taking into account the channels through which individuals interact with aquifer and the nonlinearilities in physical characteristics. For example, in studying the value of groundwater as natural capital, Fenichel et al. (2016) analyze the role value lost due to aquifer depletion in the Kansas portion of the High Plains Aquifer. They include a dummy variable for aquifer levels below 29.5 feet to capture the effects of lower pump rates on water consumption. However, this does not capture nonlinear changes in pump rates due to changes in aquifer levels and may underestimate the effects.

Results of the current study can also have significant implications for the interaction of aquifer depletion and climatic changes. The results suggest that declining aquifer levels can result in larger production risk as a result of lower ability to buffer against dry weather conditions during the critical stages of the growing season. Climate change is expected to change the distribution of seasonal and intra-seasonal weather variables resulting in more weather variation during a growing season and more frequent dry years. Under these conditions, the importance of groundwater aquifers is expected to increase. It is important to consider loss of buffer value when considering management policies (Taylor et al., 2013).

Finally, it is important to study the loss of buffer value for the entire High Plains Aquifer. The study area in this chapter has experienced smaller changes in saturated thickness compared to areas in Texas and southwest Kansas. Furthermore, there is more variation in the underlying aquifer characteristics, weather conditions and production function characteristics over the entire aquifer. Thus, studying the entire aquifer will provide a more complete picture of the effects of aquifer depletion on buffer value of the aquifer. Future research can further extend the methods provided in this study to better capture the effect of aquifer depletion on production risk in irrigated agriculture.

4.6 Tables and Figures

Table 4.1: Distribution of maximum irrigated yield across counties

Statistic	N	Mean	St. Dev.	Min	Max
Ratio of maximum irrigated yield	5	0.995	0.017	0.97	1.01

Table 4.2: Effect of saturated thickness on well capacity

	Pump rate
log(saturated thickness)	74.588***
	(1.562)
Specific yield	7.011***
	(0.348)
Constant	406.783***
	(10.917)
Year dummies?	Yes
Observations	43,981
R^2	0.098
Adjusted R^2	0.097
Residual Std. Error	303.114 (df = 43942)
F Statistic	125.890*** (df = 38; 43942)
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 4.3: Loss of buffer value for the study area

Variable	Chase	Perkins	Dundy	Sherman	Cheyenne
Irrigated acres[a]	131,100	110,522	64,188	59,412	24,842
Total annual loss (Million $)	3.28	2.73	1.93	1.82	0.83
Annual loss per acre ($)	25	24.7	30.1	30.6	33.5
Irrigated land rent ($)	172	137	126	124	111

[a] Irrigated acres for each county is the average between 2001 and 2009.

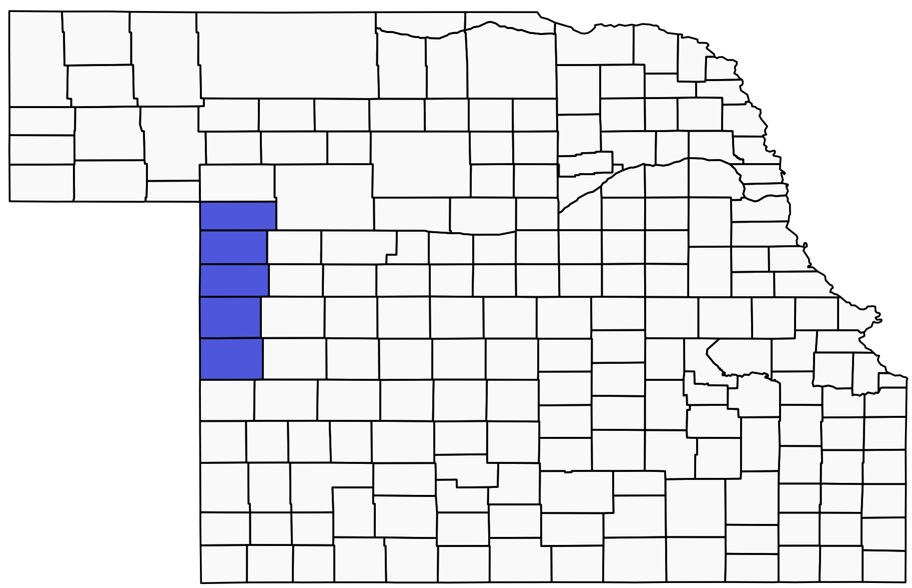


Figure 4.1: Map of the 5 counties studied. The upper 3 counties are Perkins, Chase and Dundy in Nebraska and bottom 2 counties are Cheyenne and Sherman in Kansas.

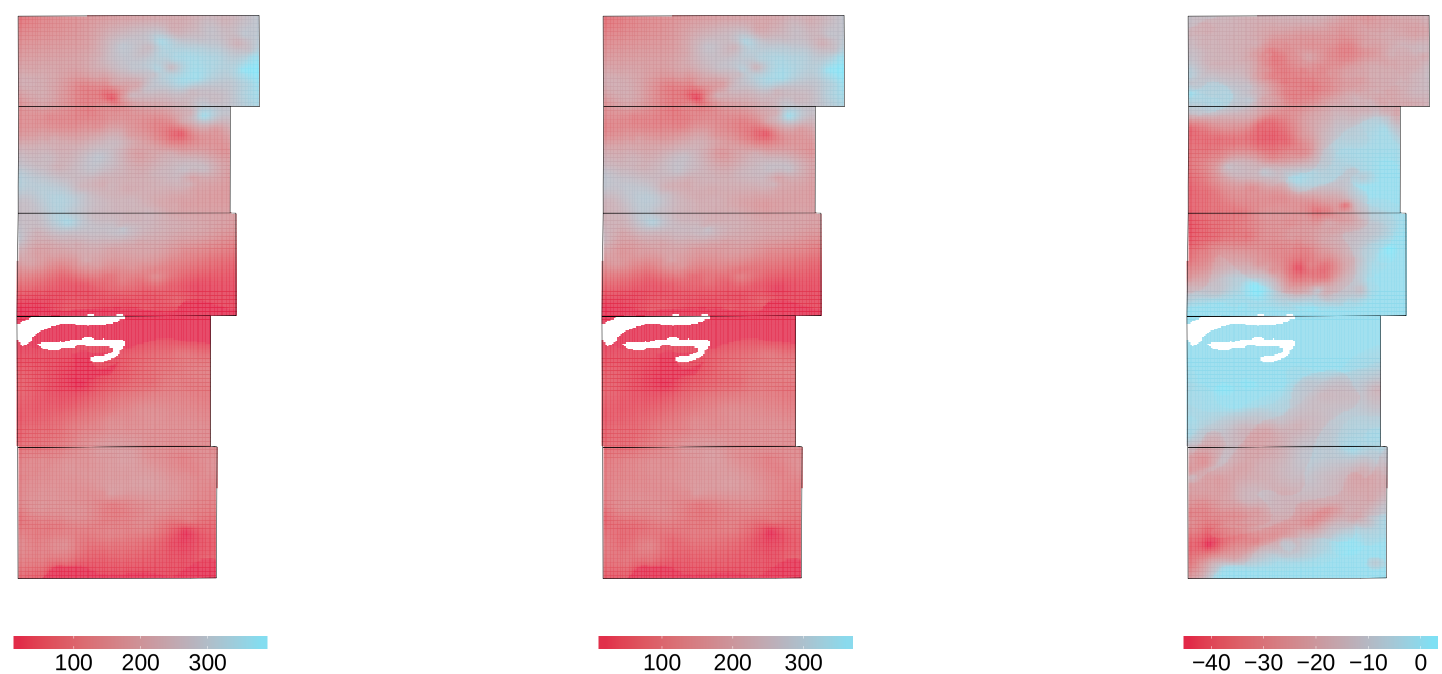


Figure 4.2: Figure shows saturated thicknesses in 1980 (left), 2009 (middle), and change in saturated thickness from 1980 to 2009 (right) in feet.

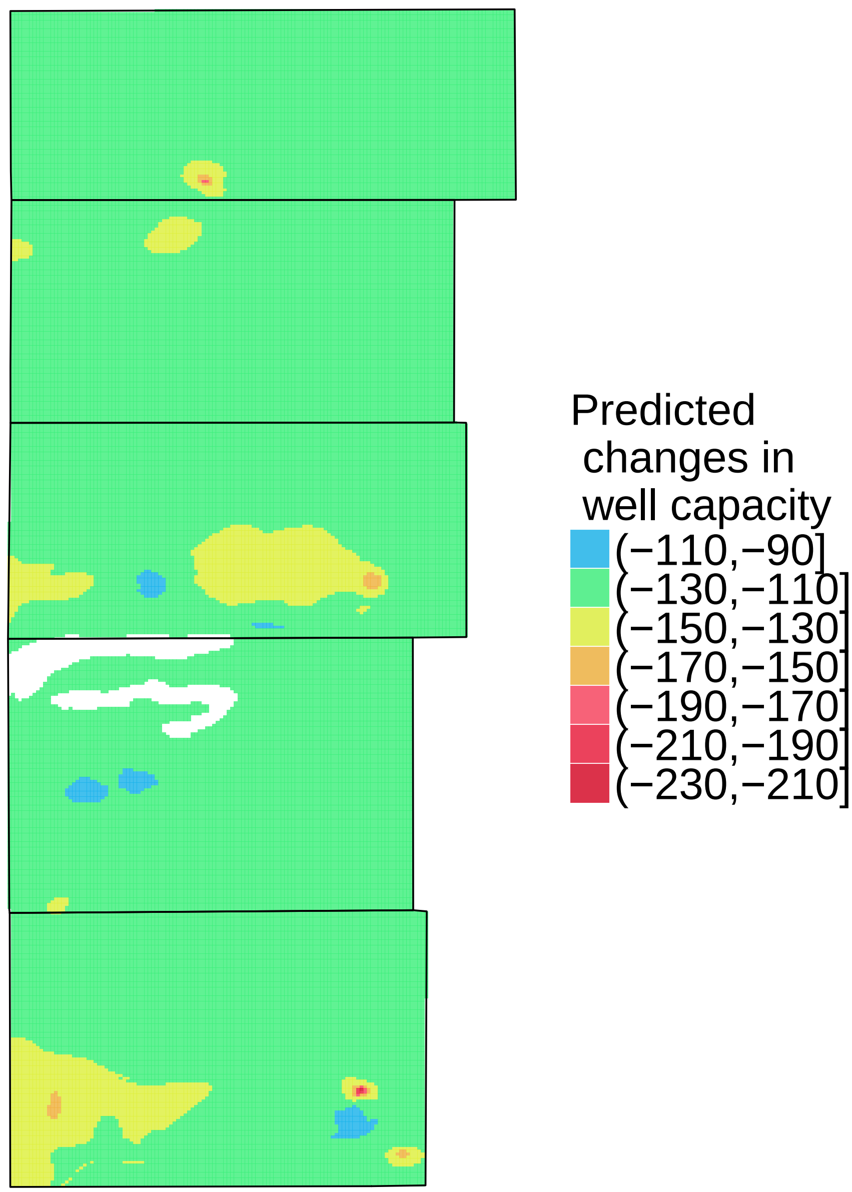


Figure 4.3: Predicted changes in well capacity in gallons per minute as a result of changes in saturated thickness in the study area between 1980 and 2009.

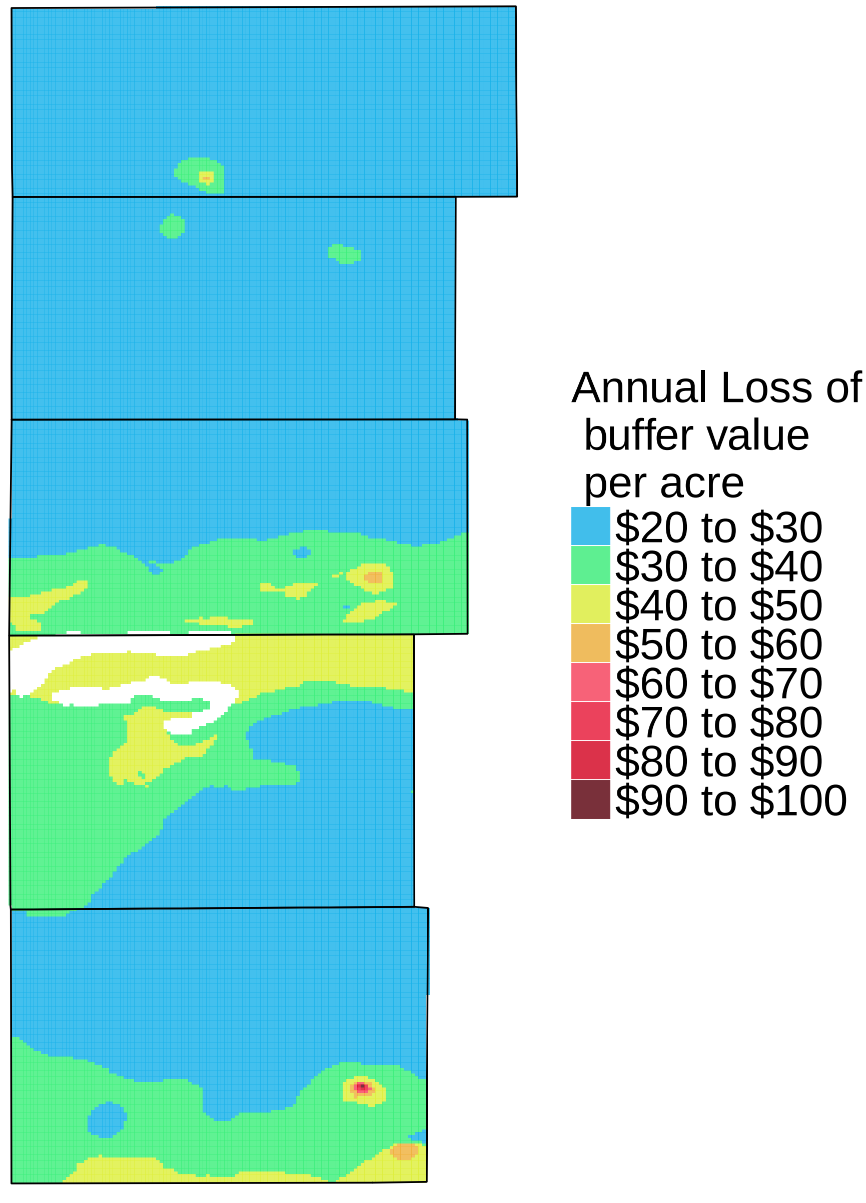


Figure 4.4: Loss of buffer value in the study area in dollars per acre.

CHAPTER 5

CONCLUSION

In this dissertation, I address the role of two important factors in water management policies in agriculture including limitations imposed by institutional settings (Chapter 2) and limitations imposed by physical aquifer characteristics (Chapter 3 and Chapter 4). I study these factors by explicitly considering the channels through which physical characteristics affect individual decisions and by studying the incentives that specific institutional settings provide for individuals. I show that the studied limitations can have a significant role in the effectiveness and distributional effects of policies and can affect the choice of policies intended to reduce extraction of resources.

In Chapter 2, in an empirical study and using a geocoded dataset that includes parcel specific characteristics, I studied whether a groundwater market with ratio trading system provides incentives for individuals to move the resource away from a surface body, namely the Platte River. The results provide evidence regarding the incentives that the market provides for moving groundwater extraction away from the river and reducing extraction over time in practice. I show that while the market provides incentives for sellers to sell their property rights in the direction intended by planners, it does not provide similar incentives for buyers. I suggest that one reason might be the presence of search costs in the market. I further study the presence of search costs in the market, which is local and informal, and find significant evidence that search costs are, in fact, significant and affect those with smaller quantities to trade and smaller SDF more significantly. I find the upper bound of loss of efficiency due to search frictions in the intensive margin of trade to be 39 percent of price of a groundwater permit. These results can provide some insight in design of permit markets at local level where the markets are informal. The results of this chapter suggest that while a trading ratio can potentially be an effective tool for moving the resources in a direction to reduce externality or reduce resource extraction, the presence of transaction costs can affect the performance of the market.

In Chapter 3, I studied the effects of heterogeneity in physical aquifer characteristics among individual farmers in terms of instantaneous supply of groundwater on farmers' irrigation decisions on the extensive and intensive margins. I show that well capacity affects a profit maximizing farmer's irrigation decisions nonlinearly such there exists a specific well capacity that those with lower well capacities adjust their irrigated acres to be able to buffer for variations in weather during the critical stages of the growing season. This nonlinearity has some major implications. First this finding suggests that responses to changes in price and precipitation may not be monotonic among individuals. Specifically, farmers with an intermediate range of well capacities may be the ones that are most responsive to changes in price and precipitation. Finally, I use the analytical results to study cost-effectiveness and distributional effects of four uniform second best policies in the Upper Republican Natural Resources District in Nebraska. I find that while a pumping tax can be the cost-effective second best policy, an acreage tax may provide better incentives for managing local aquifer depletion. This finding suggests that cost-effectiveness may not be the only factor policy makers would want to take into account when dealing with local aquifer depletion. While one might think that a pumping tax could be the best policy, an acreage tax can provide better incentives for farmers in parts of the aquifer with low well capacities to reduce their extraction. The results of this chapter show that considering the effects of heterogeneity in physical characteristics is very important for understanding the effectiveness of different policies.

The analytical results in Chapter 3 show that the effect of access to instantaneous groundwater supply on irrigation decisions and profits is nonlinear. This finding suggests that the effect of aquifer depletion on irrigated agriculture may be more significant than previously realized, especially if we consider changing climatic conditions and the role of aquifers in buffering against intra-seasonal weather variations. In Chapter 4, I study this issue using a numerical model for a part of the northern High Plains Aquifer. I find that aquifer depletion can result in a decrease in the buffer value of the aquifer which has not been considered before. Furthermore, I find that the effects of aquifer depletion on buffer value of the aquifer can vary significantly even within the scale of a county and can also depend on initial saturated thickness and local characteristics of the aquifer.

Combining results of Chapters 3 and 4 provides some insight into local management of groundwater aquifers. The results of Chapter 4 suggest that loss of buffer value is very localized and while parts of a county can experience small changes in buffer value, some other parts of the same county can experience much larger declines in their buffer value. As a result, local aquifer management should consider this heterogeneity within the management area. The results of Chapter 3 suggest that when low well capacities within portions of the aquifer are a major concern, an acreage tax may be preferred over other policies. Put together, these results can provide support for local level aquifer management as opposed to state level management. This might be of interest as in many cases policy makers are favoring local management areas. For example California is adopting Sustainable Groundwater Management Act (SGMA) to "provide a buffer against drought and climate change"[1].

Overall, this dissertation provides some insight into local management of natural resources. First, I show that when establishing a market to reallocate resources, adopting trading ratios based on transfer coefficient can be successful. However, search costs need to be taken into account. Search friction is something that may be present in many permit markets and policy makers should facilitate provision of information to potential buyers and sellers. Second, I show that considering heterogeneity in physical characteristics can be very important in choosing between alternative second best policies such as taxes and quotas. Finally, I show that in order to develop effective policies, we need to take into account the channels through which natural resource availability and its underlying characteristics affect decisions of individuals. Merely focusing on trends over time does not provide a picture that is of relevance to policy.

[1]http://groundwater.ca.gov

CHAPTER 6

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APPENDIX A

SUPPLEMENTAL MATERIALS FOR CHAPTER 2

A.1 Effects of Parcel Specific Characteristics, Prices and Precipitation on Profit Differential

Caswell and Zilberman (1986) introduced a framework to study the effects of well depth and soil quality on irrigation technology adoption decision. They study conditions under which a profit maximizing farmer would choose to use modern irrigation technologies over traditional technologies. This part builds on their study and tries to explain how physical and spatial characteristics affect farmers' profit differential and thus their reservation price. This section assumes that water rights are defined per acre[1].

Let water use efficiency, $h_i(\mu)$, be a fraction of precipitation plus water applied to the land that is utilized by crop. let land quality, μ, be water use efficiency of the soil under no irrigation. Let $i = 0$ denote dryland and $i = 1$ be irrigated agriculture. Thus by definition $h_0(\mu) = \mu$ and $h_1(\mu) > \mu$ for $\mu \in (0, 1)$ because of land quality augmenting characteristic of irrigation. Let $h_1^{'}(\mu) > 0$ and $h_1^{''}(\mu) < 0$ so that irrigation increases land quality more for lower quality soils. At $\mu = 1$, $h_1(\mu) = \mu = 1$.

Let the per acre cost of irrigation for irrigated land be cost of pumping water and fixed costs of irrigation plus operating the land. I assume that the fixed costs are independent of the amount of water applied. Pumping cost is assumed to be a linear function of applied water. For dryland farming, costs are composed of only fixed operation costs and it is assumed that the fixed

[1]In practice groundwater permits are defined in one of the two ways: assigning permits to the unit of volume of water extracted; or attaching them to the acres of land. In the former method pumps are metered while in the latter acres are monitored but there are no restrictions on the amount pumped from any certified acre. This study uses the latter to be consistent with the definition of permits in the study area.

costs of irrigating are higher than fixed costs of not irrigating[2]. With this definition, costs of irrigated and dryland agriculture are:

$$C^1(.) = p_e e \gamma x(.) + K_1 \quad (A.1)$$

$$C^0(.) = K_0 \quad (A.2)$$

where p_e is the price of energy, e is the amount of energy needed to lift one unit of water one unit of depth, γ is the depth to water and $x(.)$ is the amount of water pumped (and applied) to the land. As mentioned $K_1 > K_0$. Production function is defined as a concave function and is assumed to be the same for dryland and irrigated agriculture:

$$f^1(.) = f(e_1) = f\big(Zh_0(\mu) + x(.)h_1(\mu)\big) \quad (A.3)$$

$$f^0(.) = f(e_0) = f\big(Zh_0(\mu)\big) \quad (A.4)$$

where Z is the average amount of precipitation. e_0 and e_1 are effective water, i.e. the amount of water utilized by crop in dryland and irrigated agriculture respectively. Notice that irrigation does not augment the quality of soil in utilizing precipitation. From equations (A.1) to (A.4) we can get the per acre profit functions:

$$Max\ \pi^1(.) = Pf\big(Zh_0(\mu) + x(.)h_1(\mu)\big) - p_e e \gamma x(.) - K_1 \quad (A.5)$$

$$Max\ \pi^0(.) = Pf\big(Zh_0(\mu)\big) - K_0. \quad (A.6)$$

Since the rights are defined on the acres of land being irrigated we can find the optimal per acre amount of applied water by maximizing per acre profits:

$$\underset{x(.)}{\text{Maximize}} \quad Pf\big(Zh_0(\mu) + x(.)h_1(\mu)\big) - p_e e \gamma x(.) - K_1 \quad (A.7)$$

[2]Based on crop budgets from University of Nebraska, Lincoln extension total per acre costs for dryland getting 125 bushels actual yield per acre of corn are $444.87, while total per acre costs for center pivot irrigation getting 225 bushels actual yield per acre of corn is $944.88. Total cost of pumping is estimated to be $104.31. Thus fixed costs of irrigation (in the sense defined in this study) are much higher than those of dryland.

The first order conditions are:

$$Ph_1(\mu)f^{'}(Zh_0(\mu)+x(.)h_1(\mu))-p_e e\gamma \;=\; 0 \tag{A.8}$$

Or

$$Pf^{'}\big(Zh_0(\mu)+x(.)h_1(\mu)\big) \;=\; \frac{p_e e\gamma}{h_1(\mu)} \tag{A.9}$$

Equation (A.8) shows that there is a specific level of applied water per acre $x^*(P, p_e, \mu, \gamma, Z, e)$ that maximizes per acre profits of irrigation and equation (A.9) shows that the value marginal product (VMP) of effective water is equal to price of effective water. An increase in price of effective water would result in a decrease in amount of water applied, $x(.)$. Since irrigation increases both revenues and costs, the question is under what conditions profit of irrigation is bigger than dryland farming. The comparative statics are derived to explain the effect of parcel specific characteristics (well depth and land quality), market forces (prices of diesel and output), and climatic conditions (precipitation) on profit differential.

Well depth only affects profit of irrigated agriculture. Taking the derivative of π^1 with respect to γ we have:

$$\frac{\partial \pi^1(.)}{\partial \gamma} \;=\big[Pf^{'}h_1(\mu)-p_e e\gamma\big]\frac{\partial x(.)}{\partial \gamma}-p_e e x(.) = \; -p_e e x(.) \tag{A.10}$$

where the term in brackets is zero from the envelop theorem. Equation (A.10) shows that as well depth increases, irrigation cost increases and profit of irrigation decreases. When well depth is zero, $\gamma = 0$, profits of irrigated agriculture is greater than profits of dryland agriculture, $\Delta\pi > 0$, but as depth of well increases costs of irrigation go up, decreasing the profit differential between irrigated and dryland agriculture until at one specific well depth profits are equal. After this point irrigation does not make economic sense and the farmer sells the irrigation rights. Since at lower depths profit differential is higher we expect the farmers with lower depths to be less likely to sell and more likely to buy the rights.

Land quality increases profits of both irrigated and dryland agriculture. Since irrigation increases water use efficiency at a decreasing rate we expect that at a specific land quality profit differential is maximum. Taking the derivative of $\Delta\pi$ with respect to μ we have:

$$\frac{\partial \Delta\pi(.)}{\partial \mu} = P.\Big\{f^{'}\big(Z\mu + h_1 x(.)\big)\big[Z + x(.)h_1^{'}\big] - f^{'}(Z\mu)Z\Big\}. \quad \text{(A.11)}$$

For low land qualities, $h_1(\mu)$ is low and $h_1^{'}(\mu)$ is high. Since price of effective water is high for low land qualities, their marginal value product is high and thus $\frac{\partial \Delta\Pi}{\partial \mu} > 0$ i.e. profit differential decreases as soil quality decreases. For high land qualities, $h_1(\mu)$ is high (it is equal to 1 at the maximum point) and $h_1^{'}(\mu)$ is low (it is equal to zero when $h_1(\mu) = 1$). This means price of effective water is low and thus VMP of irrigation is low. For very high soil qualities $\frac{\partial \Delta\Pi}{\partial \mu} < 0$, i.e. as soil quality increases profit differential decreases. There is a soil quality, μ^*, between highest and lowest soil qualities that has the maximum profit differential. Farmers with low and high quality soils are most likely to sell while farmers with medium quality soils are least likely to sell. On the other hand, buyers with medium soil quality are most likely to buy and those with high and low soil qualities are least likely to buy.

Since price of output only affects the revenues and because the output of irrigated agriculture is always higher than dryland agriculture we would expect a higher price of output to increase the profit differential. On the other hand an increase in price of fuel only increases costs of irrigation and reduces the profit differential:

$$\frac{\partial \Delta\pi(.)}{\partial P} = f\big(Z\mu + h_1 x(.)\big) - f(Z\mu) \quad \text{(A.12)}$$

$$\frac{\partial \Delta\pi(.)}{\partial p_e} = -e\gamma x(.). \quad \text{(A.13)}$$

For any positive amount of applied water $\frac{\partial \Delta\pi}{\partial P}$ is positive and $\frac{\partial \Delta\pi}{\partial p_e}$ is negative, i.e. as price of output goes up or price of energy goes down the profit differential for every soil quality of sellers and buyers goes up. Finally to see the effects of changes in average precipitation, Z, on the profit differential the partial derivative with respect to Z is taken:

$$\frac{\partial \Delta\pi(.)}{\partial Z} = \big[Pf^{'}\big(Z\mu + h_1 x(.)\big) - Pf^{'}(Z\mu)\big]\mu. \quad \text{(A.14)}$$

The optimal amount of effective water for irrigated agriculture does not depend on precipitation. Thus for a given soil quality two cases can happen: if the amount of precipitation is low, VMP of irrigation is higher than VMP of dryland and an increase in precipitation increases profit differential; if the amount of precipitation is high then VMP of irrigation is lower than VMP of dryland and as precipitation increases profit differential decreases.

Prices and precipitation have a direct and an indirect effect on participation: they directly affect reservation prices through profit differential and indirectly affect reservation prices by affecting the reservation price of the other side of the market. As argued earlier mathematically the effect is ambiguous but labor market literature suggest that the effect of other side's participation is significant on one's trading activity.

APPENDIX B

SUPPLEMENTAL MATERIALS FOR CHAPTER 3

B.1 Proofs

Proposition 1. As $X \to \infty$, $G(\frac{X}{A}, \epsilon) \to 1$ and $h(X) \to \infty$ so the total water availability constraint does not bind and the objective function becomes:

$$A\left\{\Phi(u, \mu + \epsilon, \sigma) - \Gamma(Y)u\right\} \tag{B.1}$$

which is linear in the proportion of acres irrigated. At any positive u where profits per acre are positive, $A = 1$. When $A = 1$ objective function is concave in u over $[\mu + \epsilon, \infty)$, which means there exists a unique solution, u^*_∞ for the first order conditions:

$$\Phi'(u*_\infty, \mu + \epsilon, \sigma) = \Gamma(Y) \tag{B.2}$$

We can see that as marginal cost, $\Gamma(Y)$, increases, u^*_∞ decreases.

Proposition 2. Assume that there exists a X_c large enough so that $A = 1$ constraint still binds. Two sets of equations explain the case where $X > X_c$:

$$\lambda_2 = \left\{G(\frac{X}{A}, \epsilon) - (\frac{X}{A})G'(\frac{X}{A}, \epsilon)\right\}\Phi(u, \mu, \epsilon, \sigma) - \Gamma(Y)u \tag{B.3}$$

and

$$G(\frac{X}{A}, \epsilon)\Phi'(u, \mu + \epsilon, \sigma) - \Gamma(Y) = 0 \tag{B.4}$$

From equation B.3, we can see that at infinity λ_2 is positive, which means $A = 1$ is binding and with large enough X_c, λ_2 will still be greater than zero. From equation B.4 we can see that as well capacity decreases, optimal water application rate decreases at the rate:

$$\frac{\partial u}{\partial X} = -\frac{G'(\frac{X}{A}, \epsilon)\Phi'(u, \mu + \epsilon, \sigma)}{G(\frac{X}{A}, \epsilon)\Phi''(u, \mu + \epsilon, \sigma)} > 0 \tag{B.5}$$

along the concave region of the production function. This is because a change in well capacity affects the marginal profit of adding an inch, i.e. as well capacity decreases the marginal benefit of adding an inch decreases.

Proposition 3. To see how a decrease in well capacity affects shadow value of adding an acre, we take the derivative of equation B.3 with respect to X:

$$\begin{aligned}\frac{\partial \lambda_2}{\partial X} = &-(\frac{X}{A})G''(\frac{X}{A}, \epsilon)\Phi(u, \mu, \epsilon, \sigma) \\ &+ \left\{G(\frac{X}{A}, \epsilon) - (\frac{X}{A})G'(\frac{X}{A}, \epsilon)\right\}\Phi'(u, \mu, \epsilon, \sigma)\frac{\partial u}{\partial X} - \Gamma(Y)\frac{\partial u}{\partial X}\end{aligned} \tag{B.6}$$

where the first term is the effect of a change in well capacity on shadow value of adding an acre keeping the amount of water applied fixed, i.e. the effect only through a change in productivity due to instantaneous groundwater availability. The second term is the effect of a change in water application from a marginal change in well capacity (intensive margin adjustment), and the last term is the change in per acre cost of applying water. Again, we can see that as $X \to \infty$, $\frac{\partial u}{\partial X} \to 0$ and $\frac{\partial \lambda_2}{\partial X} > 0$. All three terms in equation B.6 are positive which means that as well capacity decreases both marginal benefit of adding an acre and marginal cost of adding an acre decrease. However, we know that eventually marginal benefit decreases at a much faster rate due to the concavity of production function while marginal cost decreases at a fixed rate. Thus, there exists a well capacity, X_s, where $A = 1$ does not bind anymore. This well capacity is the intersection of the two hyperplanes with $\lambda_2 = 0$ and $A = 1$. We call this point the switching point, and it is defined by the following equations:

$$\left\{G(X_s, \epsilon) - (X_s)G'(X_s, \epsilon)\right\}\Phi(u, \mu, \epsilon, \sigma) - \Gamma(Y)u = 0 \tag{B.7}$$

and

$$G(X_s, \epsilon)\Phi'(u, \mu + \epsilon, \sigma) - \Gamma(Y) = 0. \tag{B.8}$$

Equation B.8 provides a unique u^* for any X at $A = 1$. Replacing u^* into equation B.7 we get a unique $X_s(Y, \epsilon, \mu, \sigma)$. To see the change in optimal irrigation decision for well capacities below X_s we first need to assume that the second derivative of $G(X, \epsilon)\Phi(u, \mu+\epsilon, \sigma)$ with respect to both A and u is negative, and the Hessian is negative definite. This assumption provides the unique solution to the profit maximization. We then take partial derivative of both equations in 3.3 under the condition of $\lambda_1 = \lambda_2 = 0$. Differentiating the first equation of 3.3 we get:

$$\begin{aligned} &-(\frac{X}{A})(\frac{A - XA'}{A^2})G''(\frac{X}{A}, \epsilon)\Phi(u, \mu, \epsilon, \sigma) \\ &\quad + \left\langle \left\{ G(\frac{X}{A}, \epsilon) - (\frac{X}{A})G'(\frac{X}{A}, \epsilon) \right\} \Phi'(u, \mu, \epsilon, \sigma) - \Gamma(Y) \right\rangle u' = 0 \end{aligned} \tag{B.9}$$

where $A' = \partial A/\partial X$ and $u' = \partial u/\partial X$. From the second equation in 3.3 we get:

$$\begin{aligned} A' \left\{ G(\frac{X}{A}, \epsilon)\Phi(u, \mu, \epsilon, \sigma) - \Gamma(Y) \right\} + \\ (\frac{A - XA'}{A^2})G'(\frac{X}{A}, \epsilon)\Phi'(u, \mu, \epsilon, \sigma) + \\ AG(\frac{X}{A}, \epsilon)\Phi''(u, \mu, \epsilon, \sigma)u' = 0 \end{aligned} \tag{B.10}$$

The first term in B.10 is zero from first order conditions while the second and third terms are both positive. There are two possible cases. First, if $\partial u/\partial X = 0$ and $\partial A/\partial X = A/X$; second, if $A - XA' < 0$. In either case, the solution to equation B.10 should solve equation B.9. We can see from equation B.9 that only the first scenario can provide a solution to equation B.9. suggesting that when well yield is less than the switching point, the number of acres irrigated decrease while per acre amount of water applied stays the same. Notice that:

$$\frac{\partial A}{\partial X} = \frac{A}{X} \rightarrow E_{XA} = \frac{\partial A/A}{\partial X/X} = 1 \tag{B.11}$$

Where E_{XA} can be defined as elasticity of irrigated acres as well capacity changes by 1 percent. This elasticity is fixed for well capacities below X_s suggesting that changes in well capacity translates into changes in irrigated acres for well capacities below X_s.

Proposition 4. Part (a) of the proposition is directly obtained from previous propositions and does not require a proof. The proof of part (b) is straight forward. If sensitivity to daily water availability is held constant, the problem reduces to:

$$\begin{aligned}
&\underset{A,u}{\text{Max}} && A\left\{\hat{G}\Phi(u, \mu + \epsilon, \sigma) - \Gamma(Y)u\right\} \\
&\text{subject to} && Au \leq h(X) \\
& && A \leq 1 \\
& && A, u \geq 0
\end{aligned} \tag{B.12}$$

As well capacity decreases, at some well capacity $Au = h(X)$ below which the farmer adjusts the intensive margin first until the point where shadow price of adding an acre becomes zero. At that point the profit maximizing decision is to keep the amount of water applied fixed and decrease irrigated acres. This switching point is a result of seasonal water availability.

Proposition 5. In order to prove this proposition we first show that as sensitivity to daily water availability increases switching point well capacity, X_s, increases, while, u^*_∞ and u^*_{min} do not change. It is clear from proposition 1 that as well capacity reaches infinity, sensitivity to daily water availability does not affect irrigation decisions, i.e. u^*_∞ is the same for any sensitivity at infinity. Rewriting equation 3.3 for two crops, i and j, with the same seasonal production function but different sensitivity to instantaneous water availability we get:

$$\left\{G_i(\frac{X}{A_i},\epsilon)-(\frac{X}{A_i})G_i'(\frac{X}{A_i},\epsilon)\right\}\frac{\Phi(u_i,\mu+\epsilon,\sigma)}{u_i}=$$
$$\left\{G_j(\frac{X}{A_j},\epsilon)-(\frac{X}{A_j})G_j'(\frac{X}{A_j},\epsilon)\right\}\frac{\Phi(u_j,\mu+\epsilon,\sigma)}{u_j}= \tag{B.13}$$
$$G_i(\frac{X}{A_i},\epsilon)\Phi'(u_i,\mu+\epsilon,\sigma)=G_j(\frac{X}{A_j},\epsilon)\Phi'(u_j,\mu+\epsilon,\sigma)=\Gamma(Y)$$

from equation B.13, $u_i = u_j = u^*_{min}$. Since u^*_{min} is the same for all the crops with the same seasonal production function, at the switching point, where $A = 1$, we must have $G_i(X_{si}) = G_j(X_{sj})$. Since crop j is more sensitive to daily water availability, $X_{sj} > X_{si}$. This result shows that as the crop becomes more sensitive to daily water availability, a farmer switches earlier to keep the maximum daily water availability per acre at a higher rate so that she can meet the demand during critical days of the season. However, the seasonal amount of water applied below the switching point is the same for both crops. In a sense, the farmer applies more water during peak demand days for the more sensitive crop but total seasonal water application is the same for both crops. This result also suggests that as sensitivity to daily water availability increases, the error the previous models produce in explaining irrigation decisions increases. From this result, proving proposition 5 becomes straight forward. Define $\bar{X}$ such that $h(\bar{X}) = u^*_{min}$. There exists a sensitivity to daily water availability, $\bar{G}$, where switching point takes place at the point $(\bar{X}, h(\bar{X}))$. For any crop less sensitive to daily water availability than $\bar{G}$ total seasonal water availability constraint binds.

B.2 Comparative Statics

Comparative Statics 1. To see the effect of an increase in cost of pumping on per acre application rate, we take the derivative of B.4 with respect to $\Gamma(Y)$:

$$\frac{\partial u}{\partial \Gamma(Y)} = \frac{1}{G(X,\epsilon)\Phi''(u,\mu+\epsilon,\sigma)} < 0 \tag{B.14}$$

and similarly for $\dfrac{\partial \tilde{X}}{\partial \Gamma(Y)}$, we have:

$$\frac{\partial \tilde{X}}{\partial \Gamma(Y)} = \frac{\left\{\left[G(\tilde{X},\epsilon) - (\tilde{X})G'(\tilde{X},\epsilon)\right]\Phi'(u,\mu,\epsilon,\sigma) - \Gamma(Y)\right\}\frac{\partial u}{\partial \Gamma(Y)} - u}{(\tilde{X})G''(\tilde{X},\epsilon)\Phi(u,\mu,\epsilon,\sigma)} \tag{B.15}$$

since $\dfrac{\partial u}{\partial \Gamma(Y)}$ is small, the numerator is negative. Since the denominator is also negative, $\dfrac{\partial \tilde{X}}{\partial \Gamma(Y)}$ is positive meaning as cost of pumping increases switching point increases.

Comparative Statics 2. We first show the effect of a drier weather on profit-maximizing quantity of water applied per acre. As before, we take the derivative of B.4 with respect to ϵ:

$$\frac{\partial u}{\partial \epsilon} = -\frac{G(X,\epsilon)\frac{\partial \Phi'(u,\mu+\epsilon,\sigma)}{\partial \mu} + \frac{\partial G(X,\epsilon)}{\partial \epsilon}\Phi'(u,\mu+\epsilon,\sigma)}{G(X,\epsilon)\Phi''(u,\mu+\epsilon,\sigma)} \tag{B.16}$$

where the first term in the numerator shows the effect of drier weather on marginal benefit of adding a unit of water by increasing seasonal water demand, while the second term shows the effect of drier weather on marginal benefit of adding a unit of water through daily water availability. The first term in the numerator of equation B.16 is positive showing that as weather gets drier, marginal benefit of adding a unit of water over the season increases. Second term in equation B.16 is negative suggesting that as weather gets drier, marginal benefit of adding a unit of water can decrease. The intuition is that, with limited well capacity a farmer is not able to meet the demand during the critical stages of crop growth when water availability matters in a dry year. As a result, applying more water after the peak demand, when the crop yield has already suffered, has less effect on yield than when the demand is fully met. Obviously, we do not expect this effect to be significant for high well capacities. We expect water application, u, to be dominated by seasonal water demand. This is obvious from $\frac{\partial G(X,\epsilon)}{\partial \epsilon}$, which approaches zero for large well capacities. However, as well capacity decreases, $\frac{\partial G(X,\epsilon)}{\partial \epsilon}$ decreases (because its negative) and $\frac{\partial u}{\partial \epsilon}$ becomes negative suggesting profit-maximizing quantity of groundwater applied can increase in a wet year for lower well capacities. This result suggests that while a profit-maximizing farmer with high well capacities applies more water per acre in a dry year, with lower well capacities, she might apply less groundwater per acre in a dry year. This is provided in figure B.1 which shows irrigation depth for a wet year and a dry year compared to the average year for different well capacities.

In order to see the effect of a drier year on the switching point, we look at the effect of a change in ϵ on shadow value of adding an acre, equation B.3, when $A = 1$:

$$\begin{aligned}\frac{\partial \lambda_2}{\partial \epsilon} = \left\{\frac{\partial G(X,\epsilon)}{\partial \epsilon} - X\frac{\partial G'(X,\epsilon)}{\partial \epsilon}\right\}\Phi(u,\mu,\epsilon,\sigma) + \\ \left\{\left\{G(X,\epsilon) - XG'(X,\epsilon)\right\}\Phi'(u,\mu,\epsilon,\sigma) - \Gamma(Y)\right\}\frac{\partial u}{\partial \epsilon} + \\ \left\{G(X,\epsilon) - XG'(X,\epsilon)\right\}\frac{\partial \Phi(u,\mu,\epsilon,\sigma)}{\partial \mu}\end{aligned} \tag{B.17}$$

The first term is the effect of a drier weather on marginal benefit of adding an acre through daily water availability, and it is negative for two reasons. First, as the weather gets drier, keeping the amount of water applied and maximum daily application rate fixed, crop yield will decrease. Second, adding an acre results in lower maximum daily application rate per acre. As weather gets drier, the effect of lower maximum daily water available on crop yield becomes more significant. These two effects together mean that as weather gets drier, shadow value of adding an acre decreases due to inability to meet daily crop water demand. The second term in equation B.17 is the effect of seasonal water demand in a drier on shadow value value of adding an acre. As we saw, seasonal water demand increases for high well capacities and decreases for low well capacities. Thus for high well capacities, shadow value of adding an acre decreases and for low well capacities, it increases. Finally, the last term, shows the effect of a drier weather keeping seasonal application and maximum daily application rate fixed. Keeping everything fixed, in a drier year, shadow value of adding an acre is lower and the last term is negative. For high well capacities, all three terms are negative, suggesting that shadow value of adding an acre decreases for any high well capacity. As well capacity becomes smaller, the second term becomes positive. However, its effect is dominated by effect of maximum daily groundwater availability (first term). Thus under all conditions, shadow value of adding an acre decreases, suggesting that under a drier weather the farmer switches at a higher well capacity.

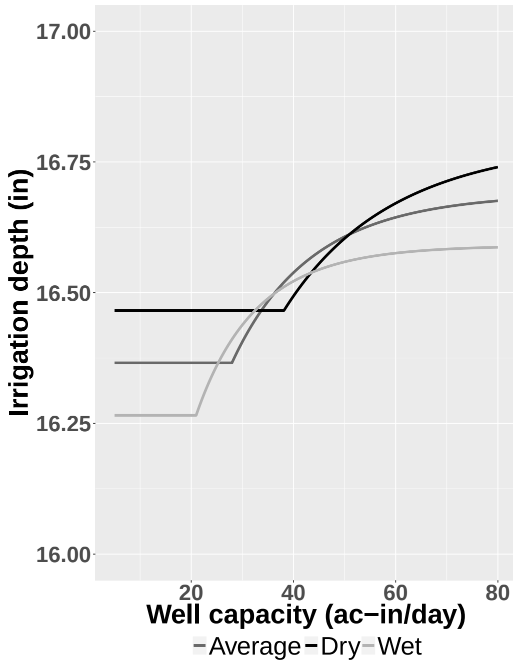

Figure B.1: Effect of climatic conditions on irrigation depth.