ISSUES INVOLVED IN GROUNDWATER WITHDRAWALS AND POLLUTION OF THE OGALLALA: EVIDENCE FROM WEST TEXAS

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OGALLALA: EVIDENCE FROM WEST TEXAS

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CHAPTER I

INTRODUCTION

Groundwater as a natural underground resource is used everywhere in the U.S., primarily as a source of drinking water supply and agriculture. Some of the largest aquifers in the country, *viz*. the Ogallala Aquifer, complement surface water requirements by providing water for irrigation, municipal and industrial areas, animal feedlots, etc. Thus, the importance of conserving groundwater, which at times is the sole source of water for agriculture or as a "buffer stock" for surface water, cannot be underestimated.

Groundwater can be a partially renewable or a nonrenewable resource. The water within the aquifer is considered a stock, while any recharge naturally through precipitation or artificially is a flow of water to the aquifer. Since the amount of recharge is highly uncertain, it becomes essential to conserve the groundwater stock to minimize the effects of the following three types of externalities contributing to inefficient pumping of water: the stock externality, the pumping cost externality, and the risk externality (Burt & Provencher, (1993, 1994). The stock externality arises due to the loss of groundwater stock available to future users of the aquifer when any agent withdraws water in the current period. Closely related to this is the pumping cost externality. The cost of pumping groundwater is inversely related to the net stock of water. Hence a unit of water extracted by an agent in the current time period will reduce the amount of groundwater stock over time and lead to a higher pumping lift (which is the distance between the ground surface and the water table). As a result, the marginal cost of extraction will increase for any user of that stock. The third externality is the risk externality. As a result of excessive pumping, the stock of groundwater gets reduced and the aquifer fails to provide stability to an agent in the event of surface water unavailability – groundwater no longer assures the agent of an effective buffer stock against drought. In addition, Provencher and Burt (1994) discuss a strategic externality where the "optimal strategy" of an agent involves pumping more water at the present so that others are excluded from maximizing the benefit of groundwater use later on.[1] Under these circumstances, the management of groundwater as a stock resource takes on a characteristic different than surface water management since its preservation now will have an impact on future users from a physical as well as an economic point of view.

The above discussion relates to the quantity aspect of groundwater management. An equally important issue that has come to the forefront during the last two decades is the deteriorating quality of groundwater from the use of fertilizers, pesticides, etc. for agricultural activities over an aquifer. In many parts of the U.S., the use of groundwater for irrigation has made it vulnerable to pollution arising from the leaching of nutrients and pesticides during production of crops. Nitrogen fertilizer is considered a major polluter—high levels of nitrogen move down from the surface and translate into nitrate in groundwater after several years, contributing to groundwater pollution. This delay in actually reaching the groundwater is driven by physiological processes that determine the movement of nutrients from the vadose zone to the surface of the water and is facilitated

[1] This externality arises even when the stock of groundwater is assumed to be infinitely large and is fallout of thepumper's reaction to stock externality ignoring any pumping cost externality (Negri,1989).

by the shallow depth of the water, low recharge, low saturated thickness of the aquifer, the presence of soil nitrogen, high levels of nitrate nitrogen (NH_3-N) fertilizer applied on the surface and several other factors. However, once the nutrient reaches water it decomposes and eventually transforms into nitrate concentrate after a period of years, depending upon the nature of groundwater and the residence time of the nutrient in the water. This nitrate then becomes a source of pollution for water withdrawn for non-agricultural users downstream.

Texas High Plains

The High Plains overlaying the Ogallala aquifer, covering a large part of West Texas has been the focus of water conservation policies for the last two decades because of rapid depletion of groundwater in this region. Irrigated agriculture constitutes almost 95% of groundwater use in most counties of the High Plains region of West Texas, with the Ogallala serving as the major aquifer. Almost complete dependence on groundwater has led to a steady depletion of the stock of water in the Ogallala with several counties like Hockley, Lubbock, Lynn and Terry resorting to large scale dry land farming. (Texas Agricultural Statistics Service (TASS) and Texas Water Development Board (TWDB)).As a result, a large number of studies beginning in the early 90's have concentrated on measures to conserve water of the Ogallala, with the primary objective being to identify appropriate management strategies that can encourage rational pumping among agents and prevent rapid depletion of the aquifer. Use of Low Energy Precise Application (LEPA) and/ or subsurface drip irrigation that minimize the loss of irrigation water, growing more drought tolerant crops, practice of conservation tillage or no-tillage, soil moisture monitoring etc. are strategies that have been pursued to conserve water of the High Plains region. Though the rise in energy cost of pumping, fall in crop prices, and use of more efficient irrigation techniques have reduced withdrawals and even helped the water level to stabilize in certain regions, counties like Lynn, Hockley, Lubbock, and Terry continue to experience declining well depths.

In recent times attention has also been focused on the pollution of the Ogallala aquifer particularly due to pesticides and fertilizers used during agricultural activities. This pollution problem translates into a twin problem for the Ogallala—the depletion problem as well as the contamination problem. The concern with nitrate pollution of the water is related to the overwhelming use of chemical fertilizers, especially inorganic nitrogen and anhydrous ammonia. Animal feedlot operations have been a source of nitrate contamination of groundwater in Castro and Parmer counties, yet irrigated agriculture remains one of the primary means of aquifer pollution in many counties of the Texas High Plains. Scientific Investigation reports by Gurdak and Qi (2006) and Reedy et al. (2007) confirm the presence of groundwater nitrate particularly due to the shallow water table and declining saturated thickness of the aquifer in most counties of the Southern High Plains. However, few studies address the groundwater quantity and quality issue as a joint resource management problem for the High Plains of West Texas. The importance of looking at the two problems conjunctively is related to the issue of the stock of water being unusable from the point of view of economic and consumptive needs before it reaches the physical exhaustion level. As Sheila Olmstead rightly points out "Water quality and water scarcity are inextricably linked (e.g., abundant water supplies have little value if pollution makes them unsuitable for wildlife, recreation, drinking, irrigation, or industrial use).[2]

In some counties of the High Plains viz. Lynn, Lubbock, Hockley, Lamb etc., nitrate concentrations much above 10mg/l have been reported in a study by Hudak (2000) as well as by investigations carried out by the Texas Water Resources Board, while a USGS Scientific Investigations Report by Gurdak and Qi (2006), puts groundwater contamination levels slightly above drinking water standards.[3] (10mg/l is the maximum concentration level of nitrates acceptable as safe as per EPA drinking water standards). Yet, until now, there has not been economic study till date that tries to address both the declining quantity and quality problems in this region. A major reason is the use of the Ogallala water solely for agricultural purposes, which overlooks the probability of future degradation of the aquifer quality that will have serious consequences for downstream water users in later years. A direct investigation of the economics involved in agricultural and municipal water use tradeoff is not the aim of this research. Instead, the study attempts to assess the quantity and quality of groundwater with reference to two counties in West Texas one of which are simultaneously facingsevere depletion problems and an increasing level of nitrate pollution of water beneath irrigated cropland. The idea is to develop a modeling structure that can solve for the optimal levels of water extraction for irrigation and the optimal level of nitrogen fertilizer application given constraints on the pumping lift, saturated thickness of the aquifer, and its gross pumping capacity.

[2]Review of Environmental Economics and Policy, volume 4, issue 2, summer 2010, pp. 179–198.

[3] More than 80% of irrigated wells in the counties of Terry and Lynn have shown nitrate concentrations that exceed the EPA MCL of 10mg/l.

The joint quantity-quality management of groundwater is something more than a rigorous insight into water conservation policies or a purely empirical exercise on regulating the nitrate pollution like any nonpoint source pollution problem. Hence the economic policy instruments explored here include policies to curtail the use of the polluting input and those that focus on reducing the use of water as well as the polluting input. The nitrate pollution problem itself is a non point source of externality. The difficulty in dealing with this is the difference in the nature of the problem from an agricultural point of view when the nitrogen is first applied to the crops and part of it percolates into the groundwater, and the resource point of view when this fertilizer actually transforms into a nitrate pollution problem downstream. There are usually five forms of economic policies in place—a uniform tax on the effluent level, a tax on the polluting input,[4] tax on ambient concentration, liability for damages and a tradable permit scheme for pollution control. In the present situation for Texas, a tax on the effluent level or on ambient concentration, a tradable permit scheme or any liability on the producers for damages is difficult to implement because the pollution problem is site specific. As a second best strategy, imposing a limit on the polluting input works well in regulating pollution as shown in Yadav (1995, 1997) for southeastern Minnesota , Mapp et al. (1993, 1994) for the Central High Plains, Fleming and Adams (1997) for Oregon and many others. Hence the study looks at a direct increase in the price of the polluting input and also evaluates the consequences of putting a restriction on its application level. Secondly, policies aimed at raising the volume of water in storage along with maintaining some level of quality are implemented. Research done on the Texas High Plains by

[4] This tax can be uniform or spatially differentiated or varied by soil types. Fleming and Adams (1997) provide a comparison in a case study in Malheur county in Oregon.

Johnson (2003), Das (2004)and Wheeler (2005, 2008) on conserving the water of the Ogallala have focused on three major types of policies—a quota on water use, a restriction on drawdown or the saturated thickness of the aquifer and water rights buyout. Willett and Sharda (1992, 1999) look at four kinds of policies to restrict the amount of irrigation water withdrawn in the Oklahoma Panhandle-these are (a) a tax on water extracted,(b) restriction on the quantity of water withdrawn, (c) a tax on water use above a definite quota (d) a water rights market.

The present study incorporates fertilizer use restriction with three specific water conservation policies. They are a quota on water use per acre, a limit on the decline in saturated thickness as an alternative to retain water in storage and finally, assessing the impact on the use of the inputs by buying out a fraction of water rights every year from the producers.

Permit trading

The second part of the research explores the consequences of permit trading through exchange of the stock of water available at any period in a two agent modeling framework. Vernon Smith in the late 1970's had proposed that water rights be assigned in proportions of both the stock and flow elements of a groundwater system. Smith referred to this as transfer of water deeds. Later Fractor (1988), Provencher (1988, 1993) and Provencher and Burt (1993) applied the concept to a private property rights regime where the stock of groundwater may be traded as private shares. This study builds on Smith's proposition for the case of the depletable Ogallala aquifer in West Texas. The role of the market price for the stock of water is to compensate the user for her conservation decisions while ensuring an efficient allocation of the water among all agents.

Broad objectives

The broad objectives of this study are as follows.

1. Identify baseline solutions for each individual county by maximizing the discounted net present value of production with constraints faced in the quantity and quality of groundwater.
2. Devise suitable management strategies through economic policy instruments such as input use restrictions, limiting the terminal stock of water to some definite level and buying out water rights for the joint quantity and quality management of groundwater.
3. Develop a set of policy recommendations by including a permit trading model based on Smith's (1977) approach of initiating water deeds or water rights in an attempt to provide an alternative to counter the rule of capture in Texas.

The study is organized as follows. Chapter II goes through a brief review of past literature dealing with management of groundwater quantity and quality. Chapter III presents a theoretical exposition of the problem. Chapter IV describes the empirical methodology followed in this research. Chapter V discusses the results while Chapter VI introduces a hypothetical model of permit trading and compares it to a myopic model with limited foresight. Finally, the conclusions and limitations of the study are taken up in Chapter VII.

CHAPTER II

LITERATURE REVIEW

Bathtub model

The earliest groundwater models were featured the bathtub concept where an aquifer was visualized as a confined unit with constant recharge. The effect of water pumped at any time period was assumed to be transmitted immediately and uniformly to all other users. Present extraction was thus a function of the stock of water that remained after the immediate past extraction by any user. In a series of papers, Gisser and Sanchez (1980, 1988, 1989) showed that the optimal extraction of water under the assumption of a bathtub model is equal to extraction in a competitive framework where users maximize profit while extracting groundwater with no concern whatsoever about the stock of water left behind. Thus the welfare difference between competitive pumping and pumping in an optimal control type of situation is minimal, indicating that any kind of external intervention is cost ineffective. This gave birth to the famous Gisser-Sanchez rule, which states that a steady-state solution for the net benefits from an optimal management of groundwater is almost similar to that of a competitive or “myopic” extraction policy given a constant return flow coefficient, deterministic recharge, known specific yield, and a known area covered by the aquifer. It should be noted that the results were obtained under the assumptions of a bottomless aquifer or without any limit to the level of water that can be extracted, moderate demand for groundwater and a high value of specific yield or area of aquifer underneath the irrigated fields or both.

Feinerman and Knapp (1983) utilized the bathtub modeling structure with linear demand for groundwater withdrawal, the latter being a linear function of the pumping lift. They estimated the benefits from reduced withdrawals and analyze the welfare consequences of changing some economic and hydrological parameters such as the discount rate, coefficients of the demand schedule, specific yield of the aquifer, and aquifer area. They found a threefold increase in benefits from groundwater management by reducing the discount rate from 5% to 3% and a 14% increase in groundwater use in an optimal control situation compared to a competitive case. Brill and Burness (1994) added a terminal value constraint for the height of the water table to the original model and found a quantitative difference in results with no such constraint in the optimal control situation. They tested the robustness of the Gisser-Sanchez rule by altering the demand specification and considering a declining well yield. While the economic depletion of the aquifer occurred before the physical exhaustion, the steady state pumping costs were found to be lower; the net present value with non-stationary demand for groundwater and declining well yield were found to be higher in the planning solution as compared to the competitive one. Burness and Brill (2001) focused on irrigation technological efficiency with groundwater use under the competitive versus planning framework. They introduced a sliding scale tax that ties water application efficiency with the tax rate so that the irrigator has an increased incentive to invest in more efficient irrigation technology to reduce pumping rates. The imposition of the tax was found to lead to an overinvestment in irrigation technology, though in the competitive case it showed a minor difference in net present benefit of around $3 million in New Mexico. The potential gain was only $7 million in the planning versus competitive case of groundwater extraction without any sliding tax. The authors attributed these results to a shorter policy horizon and the choice of the discount rate; but these show that the Gisser Sanchez rule, even under alternative scenarios, was at work.

Spatial Externalities

The Gisser-Sanchez rule breaks down when the aquifer is no longer considered a single cell or a bathtub. In defining the externalities associated with groundwater pumping, groundwater stock has been considered as a bathtub with the effect of a unit of water pumped at a particular time period being felt instantaneously and uniformly by all users through an increase in pumping lift, with no externality imposed on adjacent wells except for a reduced stock of water. However, the impact on pumping lift of a unit of water pumped today is felt now with only a time delay and is also transmitted to well owners at a finite distance from this particular pumper. The consideration of this lagged effect of groundwater withdrawal makes the management of the aquifer stock a complex issue where any regulation on pumping of water by an agent will have to take into account the time of withdrawal and the distance between his well compared to those of his neighbors. If a unit of water withdrawn by one agent affects the drawdown in a well that is at a distance of 50 miles and its own pumping lift after a delay of two to three years, then obviously pumping groundwater now has a heterogeneous impact on other users that is dependent upon users’ extraction time path over previous years and the location of the well. Herein lies the importance of exploring the temporal as well as the spatial lagged effect of pumping, analytically dealt with by the help of Theis' equation[5] by Brozovic, Sunding, and Zilberman (2002). Their propositions described how the effect of extraction from a neighboring well is directly proportional to the distance between that well and the one that is being pumped simultaneously, and also how the effect of pumping by several agents is felt only with a time lag by well(s) located miles apart. By simulating changes in storativity and transmissivity of an aquifer, they demonstrate that the bathtub model "overstates the degree of commonality between groundwater users by assuming homogeneity in the spatial effect of their pumping" (Brozovic et al., 2004). Their research directly bears on the problems faced by irrigators in the Southern High Plains in Texas. As shown by Alley and Schefter (1987), the cumulative effect of pumping by several irrigators has a greater impact on the pumping lift of an individual well in the region, though the effect diminishes with distance. On the other hand, they found that a policy of reduced withdrawal by any agent is a useful management strategy since any impact on the pumping lift through water saving policies is felt at wells in a 1,000 square mile area.

However, this type of modeling[6] —taking into account the temporal as well as the spatial dimension of withdrawing water—has been rejected by economists in favor of the bathtub type, mainly because of the failure of the Theis equation to explain regional flow modeling and also its inability to capture groundwater contamination transport across time like other purely hydrologic models. The Theis equation[7] essentially brings out the

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[5] The Theis solution can be extended to include both pumping rates that vary through time and multiple wells(Brozovic, 2002).

[6] A strategic externality kind of relationship has been explored using this bathtub analysis by Provencher and Burt(1994) and Fractor (1988) in defining a private property regime for groundwater rights.

[7] If there are J wells pumping at constant rates $u^1, u^2, \ldots, u^J$ with well j starting to pump at time t_j, then for a point that is at distance $r_1, r_2, \ldots, r_J$ from the pumping wells, drawdown at time $t > \max[t_1, \ldots, t_J]$ is given by

differences in marginal impacts over time and space from withdrawal of water at a particular well. A vast aquifer like the Ogallala with thousands of spatially interconnected wells will not experience an increase in the lift within the span of time in which any single well is being pumped. The fall in the water table for a well located at a particular point will occur with a time lag and will also be accompanied by a drawdown at adjacent well(s) a few miles apart. However, tracking the drawdown in wells across any county overlying the Ogallala becomes a regional flow process that the Theis equation is not sufficient to handle.

Studies in Texas High Plains

A set of recent studies, including a sequence of theses and dissertations on groundwater depletion in the Texas High Plains, use the bathtub type of modeling in order to examine the impact of alternate policies on groundwater conservation in the region. Feng (1992) applied a dynamic optimization model over a planning horizon to estimate the efficient path of withdrawal, marginal user cost, and irrigation technologies to be adopted. Her findings were complemented later by Johnson (2003), who found that drawdown restriction on wells stands out as an effective policy alternative, and Wheeler (2005, 2008) who concluded that while drawdown restrictions are effective economic tools in high water-use counties, water buyout policies work well in counties where a depletion problem is already in force with less acreage in irrigated production. Das's (2004) study was one of the first in its attempt to link the economic and hydrologic impacts of pumping to target spatially disaggregated locations for any policy problem. Combining a nonlinear dynamic economic model with the spatially disaggregated MODFLOW model,

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$x_t(r_1, r_1 \ldots\ldots, r_1) = \frac{u^1}{4\pi T} w(t_1, r_1) + \frac{u^2}{4\pi T} w(t_2, r_2) + \ldots \frac{u^1}{4\pi T} w(t_J, r_J)$(Brozovic et al. 2006).

Das came up with very different pumping costs and water conservation policies than conventional estimates after controlling for "aquifer heterogeneity" or an aquifer full of spatially interconnected single cells with different pumping lifts that gave an approximate county-wide base pumping lift. Das et al. (2010) developed a regional hydro economic model to examine the effectiveness of a groundwater extraction tax and extraction quotas and find that neither policy has a significant impact upon groundwater use.

Quality aspect

Groundwater management takes on a serious note when deteriorating quality of the water is a problem alongside reduced stock. In two successive papers, Roseta-Palma (2002, 2003) showed that both quantity and quality management is essential from an optimal point of view; otherwise, an optimal steady-state solution would be equivalent to a myopic or competitive solution where agents are taxed for either reducing the stock of water or worsening its quality. The stock of pollution dynamically evolves as a function of the groundwater stock and the amount of polluting input. She stressed a joint management strategy that relies on economic instruments like taxes and/or quantitative restrictions to achieve a socially optimal solution for water withdrawal and pollution.

Though Roseta-Palma's proposition based on analytical steady-state solutions approximates the optimal levels of groundwater quantity and quality, it does not capture the delayed lags involved in either the polluting input reaching the groundwater and decomposing to a contaminant or the drawdown that result from pumping water. The former has been addressed in a number of studies that specifically focus on the delay between the leaching of fertilizer and its ultimate conversion to a groundwater pollutant. Anderson, Opaluch, and Sullivan (1985) provided an early attempt at empirically modeling the relationship between pesticide application on the surface and its role as a groundwater pollutant. First they assumed a linear relationship between the application and the depth and distance of the well and then postulated a decay function for the pesticide (based on an econometrically estimable contamination function). Kim, Hostetler, and Amacher (1993)[8] and Conrad and Olson (1992) also developed water quality models where the behavior of the stock pollutant is depicted with a delayed response to the initial application of fertilizer and aldicarb respectively.

More recently, several agricultural economists placed case studies in the forefront on this aspect of pollution. Notable among them are Fleming, Adams, and Kim (1995); Yadav (1997); and Nkonya and Featherstone (2000). Yadav (1997) and Nkonya and Featherstone (2000) looked at the lagged impact on groundwater contamination by formulating the behavior of nitrate leached from corn production as a dynamic process that takes several years to transform into actual concentration. While Yadav concluded that residual nitrogen in the soil does affect the optimal rate of nitrogen application, Nkonya and Featherstone conducted simulations on various parameters affecting the flow of nitrogen as a pollutant in groundwater and called for regulation standards or education among farmers as possible management options. However, the delayed responses recognized in this research focused on the time lag for the percolation of nutrients and pesticides from the vadose zone to the aquifer but did not model their movement within the groundwater. The work of Fleming et al. (1995) concerning nitrate pollution of groundwater due to onion production in Oregon is one of very few in the economics of groundwater pollution that combined hydrological parameters with amount of nitrogen

[8] Their seminal contribution to groundwater delayed response is the employment of multistate multiple control technique incorporating Bellman's principle of optimality to derive steady-state equations of motion for groundwater stock and pollution stock

going underneath to obtain a concentration of nitrate in the groundwater. Based on this concentration, they varied economic parameters to calculate optimal tax rates and nitrogen fertilizer as input. In another paper, Fleming and Adams (1997) looked at the concentration of nitrate in groundwater to decide whether a spatial non uniform tax is superior to a uniform tax on nitrogen from irrigated agriculture in a study in Malheur County in Oregon.

The discussions above review a selected set of studies on quantity and quality of groundwater that have bothered engineers, hydrologists, and resource economists. Roseta-Palma (2003); Zeitouni and Dinar (1997); Dinar and Xepapadeas (1998); Hellegers et al. (2006), and many others have theoretically examined the quantity-quality tradeoff in groundwater and its implications for an input tax; however, they fail to empirically capture at a county level any dynamic interrelationship between changes in the pumping lift and changes in the concentration of pollution within the groundwater.[9] Lacewell et al. (1993), in their study on the Seymour Aquifer, arrived at a crop selection criterion based on nitrogen use employing simulated data and crop budgeting; however, they put more importance on optimal crop-nitrogen utilization that simultaneously maximizes a farmer’s net return and minimizes percolation and less on the extent of pollution that results. Since irrigation water and nitrogen are two essential inputs for crop production and groundwater being the source of irrigation water in almost all counties of west Texas, it becomes essential that the outcomes from their conjunctive use be economically modeled so that the well does not reach a point where it is near depletion and also economically unusable due to high levels of nitrate content. The latter situation

[9] Most of these studies are related to salinity control.

was also considered by Kim et al. (1997) as a source of nitrate in runoff/recycled groundwater that is used again for irrigation.

Research objective

The objective of our research here is to assess economic policies for managing the stock of water and preventing the accumulation of pollution stock in the eight counties of West Texas. These counties are Castro, Bailey, Parmer, Lamb, Lubbock, Hockley, Lynn, and Terry. These economic policies include actual policy instruments as well as the introduction of a water trading model. Specifically two case studies will be examined for Castro and Lubbock Counties. The study will use dynamic interrelationships between the stock of groundwater in each county and the water withdrawn for irrigation purposes as well as the quantity of fertilizer applied and the level of nitrate concentration in the Ogallala in each county to obtain base solutions for the optimal levels of irrigation water and nitrogen fertilizer applied. This will not capture the transport of the pollutant with time but will incorporate the effect of incoming nutrients on the stock of nitrate already present in the aquifer.

The research differs from past studies done on the Ogallala aquifer in Texas in the following ways. First, it will look at the problems of nitrate pollution along with groundwater extraction simultaneously. Past studies and recent research in Texas have focused on ways to conserve groundwater and prevent nitrate pollution problems as two independent areas of importance. There has been no economic study till date on the nitrate pollution problem for the Ogallala aquifer. Secondly, this will be one of the few studies for the Ogallala aquifer region that will empirically try to verify the magnitude of the twin problems for eight counties of West Texas. Studies by Zeitouni and Dinar

(1997), Dinar and Xepapadeas (1998), Hellegers and Ireland(2006) have been oriented towards California with the exceptions being that by Lacewell and Chowdhury (1993) who have looked at the pollution problem in the Edwards aquifer region in Texas. Last but not the least, this study will attempt to develop policy recommendations for dealing with the two problems that are feasible with the Texas rule of capture for groundwater. The permit trading concept for groundwater in this region is introduced following Vernon Smith's recommendation of water deeds being traded in the form of stock or flow in order to achieve efficient outcomes in water allocation.

CHAPTER III

CONCEPTUAL FRAMEWORK

Background

This chapter provides an outline of the theoretical background of a single cell aquifer model that is subjected to water extraction and pollution due to application of nitrogen fertilizer. Irrigation water and nitrogen fertilizer are assumed to be the two primary inputs for agricultural production. The nitrogen fertilizer is an input to production but is also the source of an environmental externality in the form of groundwater pollution. The pollution problem occurs due to the surface application of excess nutrients in the following manner. First a fraction of the fertilizer actually leaches into groundwater as a runoff and this is the proportion which is not absorbed by the plant root (in this case we assume this to be an agricultural runoff; the runoff particularly from surface water used for irrigation that seeps into the ground may be affected by stochastic factors depending on the level of water and the physical characteristics of the aquifer but we abstain from modeling it here). A portion of this accumulated fertilizer then undergoes transformation into nitrates, which essentially contributes to the pollution of groundwater. Thus for each unit of nitrogen applied, some portion always finds its way to the groundwater stock. Kim et al. (1993) use a discrete time dynamic programming framework to capture the pollution stock and application level at each period. In the last two decades, a continuous time optimal control framework has been commonly used to represent the dynamic time paths of motion of the pollutant over a finite time horizon. This is the approach followed here. An exhaustible aquifer is considered where the extraction of water takes place within a time period denoted by T. It is also assumed that the pollution of groundwater is not like a contamination episode but a consistent accumulation of the fertilizer over the entire time horizon starting out with an initial stock of nitrate in the water.[10] The two control variables in this model are irrigation water and nitrogen fertilizer while the two state variables are the stock of groundwater and the concentration of the pollutant at a given period of time.

The groundwater stock variable can be represented by the saturated thickness of the aquifer which is measured by the height of the water table in feet from the water level to the bottom of the aquifer. Pumping lift on the other hand is the distance between the ground surface and the water level and directly affects the marginal cost of pumping water as it influences the pump engine power requirement and hence the cost of withdrawing water from the aquifer. The pumping cost is considered to be a function of the stock of water in the aquifer and is affected by several hydrological parameters. The relationship between the pumping cost and the stock of water bears down to what is known as the economic exhaustion of an aquifer which indicates the point at which the extraction of water is "economically not profitable" due to the increased marginal cost of withdrawing water from the aquifer. This is different from the physical exhaustion of the aquifer which refers to a point where there is no physical stock of water left to be withdrawn.

[10] By contamination episode we mean a sudden influx of nitrates in the water which may result from the transportation of nitrates from a different source or nitrates accumulated in the water from the same source but at certain intervals.

Model

The emphasis here is on a group of farms N_t farmers and for simplicity it is assumed that each farm is an acre and that farmers are homogenous in their behavior towards groundwater extraction. Though soil characteristics may vary across a region, it is assumed that a dominant soils structure characterizes an area such that conditions for growing crops are more or less uniform across farms. The prices of the crop as well as the cost of a unit of nitrogen fertilizer applied are taken as constants. The decision-making time horizon is assumed to be of finite length T and a terminal value for the benefit function, $D(S_T)$ allows for the possibility that the stock of groundwater has value to thefarm beyond the current period. Moreover, the existence of the terminal value function is likely to prevent economic or physical exhaustion of the stock of groundwater rights in the terminal period T —in other words there is some benefit beyond the current decision making time period.

Let x_t be the amount of groundwater extracted by any representative farmer for growing the crop at time t, m_t be the amount of fertilizer applied for the same, S_t be the stock of water in the aquifer at time period t, C_t be the per unit marginal cost of extracting water from the aquifer at period t, M_t be the stock of nitrates in the aquifer that contributes to pollution, P_m be the per unit price of the fertilizer, η be the fraction of the fertilizer that actually seeps into groundwater (assuming no distinction between deep percolation and leaching at normal level), R be the average rate of recharge in the aquifer which is assumed to negligible, δ be the decay rate or the rate of degradation of the fertilizer once it reaches the water, M be an exogenously specified maximum concentration level of nitrate in the aquifer and finally, r be the discount rate for the calculation of the net present benefits over the planning horizon. $B(x_t, m_t)$ is the benefit function for each farmer while $l_t(x_t, m_t)$ is the leaching function or what represents the percolation of fertilizer underneath the soil as a function of the two main inputs.

The objective function with N_t farmers can be expressed as a joint maximization problem as:

$$Max \int_0^T \{[B(x_t, m_t) - C_t(S_t)x_t - P_m m_t]N_t\}e^{-rt} + D(S_T)e^{-rT} \tag{3.1}$$

Subject to:

$$\dot{S}_t = R - N_t x_t \tag{3.2}$$

$$\dot{M}_t = \eta N_t l_t(x_t, m_t) - \delta M_t \tag{3.3}$$

$$M_t \leq M \tag{3.4}$$

$$S_0 = \bar{S} \tag{3.5}$$

$$M_0 = \bar{M} \tag{3.6}$$

Here, the objective function (3.1) represents a discounted net benefit function for all farmers over the planning horizon net of pumping costs, $(C_t(S_t)x_t)$, and the total cost of fertilizer $(P_m m_t)$. $C_t(S_t)x_t$ represents the total cost of extracting groundwater. The marginal pumping cost is constant with respect to x_t but it varies with the stock of water every period. The constraint set has two state variables—the stock of groundwater at time *t* given by (3.2) and the concentration of nitrate or the stock of pollution in the groundwater given by (3.3). The equation of motion for the stock of water evolves due to the presence of some form of recharge(R) and total extraction of water $(N_t x_t)$ at the same time. However the recharge rate is assumed to very low compared to actual pumping rates so the aquifer may be considered as an exhaustible or depletable resource. The first term in the right hand side of the pollution stock equation is the actual quantity of fertilizer that leaches into the ground. The second term is the stock of nitrate that actually contributes to pollution after a proportion decays at a rate δ. Thus the dynamic equation of motion that describes the rate of change of pollution (affecting the quality of groundwater) depends on the flow of pollutant and the subsequent accumulation of the pollutant stock until time T. The final constraint (3.4) is similar to an exogenously determined limit to the stock of pollution at any time period. Equations (3.5) and (3.6) denote initial values for the state variables.

The last term in the objective function $D(S_T)$ represents the terminal value function which captures the value of the stock of water in the aquifer beyond the current decision making horizon. The addition of this term ensures that the water stock may not be exhausted within the time period under consideration and if T is of a shorter duration, the higher is the importance of this function.

The conventional method for solving the above dynamic problem is to generate the present valued Hamiltonian

$$H_t = \{B(x_t\,, m_t) - C_t(S_t)x_t - P_m m_t]N_t + \lambda_t(R - N_t x_t) + \Lambda_t[\eta N_t l_t(x_t, m_t) - \delta M_t]$$

where λ_t and Λ_t are the respective costate variables for the equation for motion of the stock of water and that of the pollutant and in the presence of (3.4) we can augment the Hamiltonian into the Lagrangian (Chiang, pp.279)

$$\mathcal{L}_t = \{B(x_t\ , m_t) - C_t(S_t)x_t - P_m m_t]N_t + \lambda_t(R - N_t x_t)$$
$$+ \Lambda_t[\eta N_t l_t(x_t, m_t) - \delta M_t] + \omega_t(C - M_t)$$

where ω_t is the multiplier for the inequality constraint (3.4). However, the presence of the constraint on the state variable given by equation (3.4) implies that the usual solution techniques cannot be used. In the normal situation when there is not a constraint such as (3.4), solution procedures are usually based on the continuity of the costate variables. However, in our case the costate variable can experience a jump if (3.4) goes from nonbinding to binding and vice versa. An alternative solution strategy must be used; the solution strategy shown in Chiang (1992, pp. 299-313) is used here. This method can be applied without transforming the original statement of the problem.

We can express M_t in (4) above as M_t= $h_t(M_t, t, \eta l_t)$.Then differentiating $h_t$with respect to time yields the following:

$$\dot{h_t} = [\eta N_t l_t(x_t, m_t) - \delta M_t] \qquad (3.7)$$

Following Chiang (1992, pp.299-313) we can form the following Lagrangian:

$$\mathcal{L}_t = \{B(x_t\ , m_t) - C_t(S_t)x_t - P_m m_t]N_t + \lambda_t(R - N_t x_t) \qquad (3.8)$$
$$+ \Lambda_t[\eta N_t l_t(x_t, m_t) - \delta M_t]$$
$$+ \theta_t[\eta N_t l_t(x_t, m_t) - \delta M_t]$$

It should be noted here that Λ_t is the costate variable for M_t and θ_t is the Lagrangean multiplier for equation (3.4) or more precisely (3.7).

The first order necessary conditions are as follows:[11]

$$\frac{\partial \mathcal{L}}{\delta x_t} = \left[B_{x_t} - C_t(S_t)\right]N_t - \lambda_t N_t + \Lambda_t \eta N_t \left(\frac{\partial l_t}{\partial x_t}\right) + \theta_t \eta N_t \left(\frac{\partial l_t}{\partial x_t}\right) \leq 0 \tag{3.9a}$$

$$x_t \frac{\delta \mathcal{L}}{\delta x_t} = 0 \tag{3.9b}$$

$$\frac{\partial \mathcal{L}}{\delta m_t} = \left[B_{m_t} - P_m\right]N_t + \Lambda_t \eta N_t \left(\frac{\partial l_t}{\partial m_t}\right) + \theta_t \eta N_t \left(\frac{\partial l_t}{\partial m_t}\right) \leq 0 \tag{3.10a}$$

$$m_t \frac{\delta \mathcal{L}}{\delta m_t} = 0 \tag{3.10b}$$

$$-\frac{\partial \mathcal{L}}{\delta S_t} = \dot{\lambda}_t - r\lambda_t = C'_t(S_t)N_t x_t \tag{3.11}$$

$$-\frac{\partial \mathcal{L}}{\delta M_t} = \dot{\Lambda}_t - \mathrm{r}\Lambda_t == -[\Lambda_t(-\delta) + \theta_t(-\delta)] \tag{3.12}$$

$$\frac{\delta \mathcal{L}}{\delta \theta_t} = \eta N_t l_t(x_t, m_t) - \delta M_t \geq 0 \tag{3.13}$$

$$\theta_t \geq 0 \ \theta_t . \frac{\delta \mathcal{L}}{\delta \theta_t} = 0 \tag{3.14a}$$

$$\theta_t[\eta N_t l_t(x_t, m_t) - \delta M_t] = 0 \tag{3.14b}$$

$$\dot{\theta}_t < 0 \text{ when } M_t = C$$

$$\dot{\theta}_t = 0 \text{ when } M_t < C \tag{3.14c}$$

[11] Please refer to Dynamic Optimization by Alpha C. Chiang (1992, pp. 278-279 and pp: 299-313) for discussions on these.

$$\frac{\delta \mathcal{L}}{\delta \lambda_t} = \dot{S}_t = R - N_t x_t \geq 0 \tag{3.15}$$

$$\frac{\delta \mathcal{L}}{\delta \Lambda_t} = \dot{M}_t = \eta N_t l_t(x_t, m_t) - \delta M_t \geq 0 \tag{3.16}$$

The following transversality condition also apply (T when assumed to be fixed as is in our case)

$$D_{S_T}(S_T) = \lambda_T \tag{3.17}$$

<u>Interpretations</u>

The relevant first order conditions for our maximization problem assuming that the positive amounts of irrigation water (x_t) and fertilizer (m_t) will be applied at every period,i. e. $x_t > 0$ and $m_t > 0$ can be expressed as:

$$\left[B_{x_t} - C_t(S_t)\right] - \lambda_t + \Lambda_t \eta \left(\frac{\partial l_t}{\partial x_t}\right) + \theta_t \eta \left(\frac{\partial l_t}{\partial x_t}\right) = 0$$

or,

$$B_{x_t} = C_t(S_t) + \lambda_t - \Lambda_t \eta \left(\frac{\partial l_t}{\partial x_t}\right) - \theta_t \eta \left(\frac{\partial l_t}{\partial x_t}\right) \tag{3.18}$$

Similarly from 10(a)

$$\left[B_{m_t} - P_m\right] + \Lambda_t \eta \left(\frac{\partial l_t}{\partial m_t}\right) + \theta_t \eta \left(\frac{\partial l_t}{\partial m_t}\right) = 0$$

or,

$$B_{m_t} = P_m - \Lambda_t \eta \left(\frac{\partial l_t}{\partial m_t}\right) - \theta_t \eta \left(\frac{\partial l_t}{\partial m_t}\right) \tag{3.19}$$

The left hand side in equation (3.18) show the marginal benefits accrued from the application of a unit of irrigation water, while the right hand side equals the marginal cost of extraction plus the user cost-the latter consisting of three components. λ_t is the opportunity cost of withdrawing an unit of water at the present period. In the pollution literature$\Lambda_t \eta \left(\frac{\partial l_t}{\partial x_t}\right)$ and $\theta_t \eta \left(\frac{\partial l_t}{\partial m_t}\right)$ would represent the externalities imposed due to percolation of excess fertilizer into the water. However, that the excess fertilizer moving underground may add to net benefits for the agent as is clearly observed from (3.18). Equation (3.19) has a similar interpretation for the application of fertilizer for the crop. While the first term in the right hand side is the private cost of the fertilizer applied, the following two terms may capture the avoided costs or the potential benefits from the proportion of nitrogen fertilizer going underground. This is because a part of the fertilizer may show up in the groundwater and may be reused as a recycled nutrient later.[12] But caution should be exercised in this interpretation. When the fertilizer use exceeds a point where it actually adds to the pollution stock in the water, the benefits from using it should be weighed against the costs inherent in treating it as a polluting input. This becomes important as the pollutant stock comes to a point when the higher is the use of the input, the higher is the social cost imposed through the pollutant.

The differential equation for the co state variable λ_t is given by (3.11):

$$\dot{\lambda}_t - r\lambda_t = C'_t(S_t)N_t x_t$$

or,
$$\dot{\lambda}_t = r\lambda_t + C'_t(S_t)N_t x_t \tag{3.20}$$

Equation (3.20) shows that the rate of change of the shadow price for the stock of groundwater equals the net marginal cost of pumping and an additional term that can be interpreted as the marginal user cost of pumping that depends on the discount rate r.

[12]For a discussion on the reuse of the fertilizer refer to Kim et al. "An Alternative Specification for Modeling Groundwater Dynamics." *Natural Resource Modeling,* 10(3), pp.173-183.

These two components constitute the rate of change of the shadow price for the groundwater stock but do not tell us anything about the intertemporal nature of the time path.The inter temporal nature of $\lambda_t$can be described by the following equation (refer to the appendix for the detailed derivation).

$$\lambda_t = e^{-r(T-t)} D_{S_T}(S_T) - \int_t^T e^{-r(\tau-t)} C_\tau'(S_\tau) N_t x_\tau d\tau \qquad (3.21)$$

The two terms in the right hand side can be interpreted in a manner similar to Lyon (1999) and Lyon and Lee (2004). The first term is the scarcity effect or the scarcity rent for the use of the water stock and represents the discounted marginal value imposed on the remaining reserve or stock of water over the time period under consideration. In the language of resource economics, as long as $D_{S_T}(S_T) = \lambda_T > 0$ i.e. it is economically possible to reach an exhaustion level for the use of the groundwater, the scarcity rent is always positive. In other words we can impute a positive price to the use of the water every period. Since $C_\tau'(S_\tau) N_t x_\tau < 0$ the second term in the right hand side is positive. It is referred to as the cost effect and captures the dynamic cost savings associated with lower extraction at any period of time since groundwater extraction is inversely related with the amount of the total stock.

Going back to the marginal benefit function in (3.18), we have:

$$B_{x_t} = C_t(S_t) + \lambda_t - \Lambda_t \eta \left(\frac{\partial l_t}{\partial x_t}\right) - \theta_t \eta \left(\frac{\partial l_t}{\partial x_t}\right)$$

$$B_{x_t} = C_t(S_t) + e^{-r(T-t)} D_{S_T}(S_T, M_T) - \int_t^T e^{-r(\tau-t)} C_\tau'(S_\tau) N_t x_\tau d\tau - \{\Lambda_t \eta \left(\frac{\partial l_t}{\partial x_t}\right) + \theta_t \eta \left(\frac{\partial l_t}{\partial x_t}\right)\} \quad (3.22)$$

This implies that the marginal net benefit from water extraction equals the constant marginal cost of extraction plus the scarcity cost and the stock cost .In addition, as discussed previously, there is some benefit associated with the fertilizer percolating underneath that is captured by $\Lambda_t \eta \left(\frac{\partial l_t}{\partial x_t}\right)$ and $\theta_t \eta \left(\frac{\partial l_t}{\partial x_t}\right)$.

Two cases are in order here.

(a) θ_t =0 wherein the pollution stock is not binding at C at any time or (3.4) does not hold. Then from (3.19) we have

$$B_{m_t} = P_m - \Lambda_t \eta \left(\frac{\partial l_t}{\partial m_t}\right) \quad (3.23)$$

or,

$$\Lambda_t = \frac{P_m - B_{m_t}}{\eta \left(\frac{\partial l_t}{\partial m_t}\right)} \quad (3.23\text{-i})$$

$$B_{x_t} = C(S_t) + \lambda_t - \frac{P_m - B_{m_t}}{\eta \left(\frac{\partial l_t}{\partial m_t}\right)} \eta \left(\frac{\partial l_t}{\partial x_t}\right)$$

or,

$$B_{x_t} = C(S_t) + \lambda_t + \frac{\left(\frac{\partial l_t}{\partial x_t}\right)}{\left(\frac{\partial l_t}{\partial m_t}\right)} (B_{m_t} - P_m) \quad (3.24)$$

As evident from the expression (3.23-i), $\Lambda_t < 0$, because the numerator is negative while the denominator is positive going by our assumption that higher application of the fertilizer is conducive to higher percolation underneath. From the first order condition in (3.23), $\mathrm{B}_{\mathrm{m}_t} = \mathrm{P}_\mathrm{m} - \Lambda_t \eta \left(\frac{\partial \mathrm{l}_t}{\partial \mathrm{m}_t}\right)$. This implies that the marginal benefit for application of the polluting input equals the price of the input (direct cost) and an indirect benefit of applying it in excess as captured by the second term in the right hand side. The logic follows the discussions for (3.19). On the other hand, the right hand side of (3.24) may be shown to consist of a pumping cost or a direct cost $(\mathrm{C}(\mathrm{S}_t))$ and the imputed social costs.

Again from the FOC in (3.12),when$\theta_t = 0$

$$\dot{\Lambda}_t - \mathrm{r}\Lambda_t = \delta\Lambda_t$$

$$\dot{\Lambda}_t = (r + \delta)\Lambda_t \qquad (3.25)$$

and on substituting the value of Λ_t,

$$\dot{\Lambda}_t = (r + \delta)\frac{P_m - B_{m_t}}{\eta\left(\frac{\partial l_t}{\partial m_t}\right)} \qquad (3.25\text{-i})$$

Mathematically it is evident that $\dot{\Lambda}_t < 0$ (as long as $(\mathrm{r} + \delta)$ is positive). Intuitively, this suggests that the inter temporal shadow price for the pollutant stock diminishes over time which should be held as a general conclusion and does not rule out the need for economic instruments to prevent the accumulation of the stock.

Also from (3.11) $\dot{\lambda} = r\lambda_t + C'_t(S_t)N_t x_t$

Substituting the value of λ_t in the right hand side we can describe the time rate of change in the shadow price for the stock equation as follows:

$$\dot{\lambda}_t = r\left\{e^{-r(T-t)}D_{S_T}(S_T) - \int_t^T e^{-r(\tau-t)}C'_\tau(S_\tau)N_t x_\tau d\tau\right\} + C'_t(S_t)N_t x_t \tag{3.26}$$

For the stock of groundwater, the above equation essentially states that the rate of change of the shadow price of the stock of water is a function of the change in net cost of drawing water at that period plus the discounted values of the scarcity cost and the stock cost.

The shadow price of the pollution stock Λ_t may be expressed as: (see appendix A3 for the derivation):

$$\Lambda_t = \Lambda_0 \, \mathrm{e}^{(\mathrm{r}+\delta)t}$$

or,

$$\frac{\Lambda_t}{\Lambda_0} = \mathrm{e}^{(\mathrm{r}+\delta)t} \tag{3.27}$$

Where Λ_0 is the initial shadow price of the pollution stock. This is nothing but Hotelling's rule which states that the rate of change in the price of any depletable stock rises exponentially with the decay rate and the rate of discount. However this has a different implication for the present case. Even when the pollution stock is not binding the shadow price at any time rises exponentially at a rate equal to the sum of the social discount rate and the degradation rate.

To determine how the time path of the pollution stock will look like recall equation (3.25)

$$\dot{\Lambda}_t = (r+\delta)\Lambda_t$$

It shows that the rate of change in the shadow price of the pollution stock is a function of two parameters: (a) the discount rate and (b) the rate of degradation of the pollutant in the water. The rate of discount is an imputation of the future costs of the pollutant in the water.

(b) Now we turn to the case where the pollution constraint is binding or equation (3.4) holds as an equality. Revoking the first order conditions derived in equations (3.9a) to (3.16), this pertains to the case where$\theta_t \neq 0$.

From (3.10 a), we obtain

$$B_{m_t} = P_m - \Lambda_t \eta \left(\frac{\partial l_t}{\partial m_t}\right) - \theta_t \eta \left(\frac{\partial l_t}{\partial m_t}\right) \tag{3.28}$$

$$(\Lambda_t + \theta_t) = \frac{P_m - B_{m_t}}{\eta \left(\frac{\partial l_t}{\partial m_t}\right)} \tag{3.28-i}$$

Expression (3.28) implies that the marginal benefit from application of a unit of nitrogen fertilizer at time *t* equals the price of the fertilizer plus some foregone profits due to percolation of the nutrients underneath the soil. It should be remembered that the new term θ_t in (3.28-i) does not represent a damage function. Instead it puts a limit or a cap on the build up of the pollutant in the aquifer which gets manifested in lower application of the fertilizer in the present period. (This concept is important for it relates the non-point pollutant stock with the level of polluting input whenever the stock effect is binding. Whenever the pollution constraint is not binding, lower application of the input at present implies foregone profits. In the empirical results, a tradeoff is observed between this loss in profits and the decline in pollutant stock (Castro County) when input use is restricted which is a point source remedy. But when the use of inputs is already low so that the pollutant stock is diminishing over time, the opportunity cost of restriction in the use of the input is very high-such a case is observed for Lubbock County. So this is, essentially a site specific problem).

Utilizing the value of $(\Lambda_t + \theta_t)$above, (3.18) implies

$$B_{x_t} = C(S_t) + \lambda_t + \frac{\left(\frac{\partial l_t}{\partial x_t}\right)}{\left(\frac{\partial l_t}{\partial m_t}\right)}(B_{m_t} - P_m) \tag{3.29}$$

which is essentially the same expression obtained when the binding constraint on the pollution stock does not hold. Also as evident from (3.28-i) $(\Lambda_t + \theta_t)$ is negative implying $\Lambda_t < 0$ and $\theta_t < 0$. However, the effect on the dynamic path of the pollutant is different. Now (3.12) takes the following form:

$$\dot{\Lambda_t} - \mathrm{r}\Lambda_t = -[\Lambda_\mathrm{t}(-\delta) + \theta_t(-\delta)]$$

or,
$$\dot{\Lambda_t} = \mathrm{r}\Lambda_t - \Lambda_t(-\delta) - \theta_t(-\delta)$$

or,
$$\dot{\Lambda_t} - (\mathrm{r} + \delta)\Lambda_t = \theta_t\delta \tag{3.30}$$

After some manipulations (see appendix A4), Λ_t may be expressed as:

$$\Lambda_t = e^{-(r+\delta)(T-t)}\Lambda_T - \int_t^T e^{-(r+\delta)(\tau-t)}\,\theta_\tau\delta\, d\tau \tag{3.31}$$

Like the stock of water, we can decompose the shadow price or the co-state variable for the pollution stock into two effects that hold over time. The first term in the right hand side is the pollution abundance effect (Lyon, 1999) or the effect of the stock of pollution accumulated over the remaining years of the time period that has a negative effect on the terminal value of the pollution stock. It is balanced by the second expression which is again a cost effect like in (3.21). In economic terms it is the reduction in the pollution that may be achieved over time by applying less of the polluting input. If δ is high this term increases implying that a higher rate of degradation implies lower effect on the water quality due to the pollution stock and hence a lower opportunity cost of pollution at the present time. On the other hand, going by our former analysis in (3.28), θ_τ also captures the inability of the agent to add to her profits in farming operations and thus constitutes an indirect cost to the producer from the pollution stock. But as mentioned before, the social cost of the pollution should be borne in mind while considering the loss in producer profit.

The final derivation is associated with (3.28-i) and (3.30). Substituting the value of the former into the latter provides the following:

$$\dot{\Lambda}_t = r\Lambda_t + \delta \frac{P_m - B_{m_t}}{\eta\left(\frac{\partial l_t}{\partial m_t}\right)} \tag{3.32}$$

With the pollution constraint being binding, the rate of change of the shadow price of the pollution stock consists of two components— the first term on the right hand side is a valuation of the future costs of the pollutant. In contrast, the second term denotes the present opportunity costs of the pollutant weighted by the decay rate. It may be interpreted as the fall in the opportunity costs due to the pollutant undergoing some form of degradation in the aquifer.

Here we make a short digression by pointing out some differences in the solutions reached when (3.4) is binding and when (3.4) is not binding from the point of view of a social planner.

While $\Lambda_t = \Lambda_0 e^{(r+\delta)t}$ when (4) is not binding

$$\Lambda_t = e^{-(r+\delta)(T-t)}\Lambda_T - \int_t^T e^{-(r+\delta)(\tau-t)}\,\theta_\tau\delta\,d\tau \qquad \text{when (4) is binding}$$

Thus there is hardly an opportunity cost of application of excess nitrogen fertilizer unless the constraint (3.4) holds as equality or we come up against an environmental regulation on the maximum amount of pollution stock. However, in order to prevent the excess flow of fertilizer Λ_t can be considered as a social tax as discussed above, by imputing a finite value toΛ_0 in the initial time period and this will eventually affect the application rate of fertilizer. When (3.4) is binding, the whole expression in the right hand side of (3.31) can be considered as a form of tax rate on the polluting input at any point of time. The shadow price for the pollutant picks up an additional marginal cost of pollution in the form of $\theta_t\delta$. Following Farzin (1996, pp.41) we can conclude that the environmental scarcity rent or Λ_t is a kind of a social tax which when included in the price of the input or the fertilizer can capture the marginal external effects of the pollution.

Combining (3.30) and (3.31) we obtain:

$$\dot{\Lambda}_t = (r+\delta)[e^{-(r+\delta)(T-t)}\Lambda_T - \int_t^T e^{-(r+\delta)(\tau-t)}\,\theta_\tau\delta\,d\tau] + \theta_t\delta \qquad (3.33)$$

The above expression logically follows from the path that the co-state variable for the pollution stock assumes. While the first part of the right hand side denotes the net discounted value of the pollution abundance effect and the cost savings effect, the second term accounts for the opportunity cost of the pollution constraint being binding at any particular period. Both define the rate of change of the shadow price of the stock of pollution at any particular time period.

The analysis here does not include an environmental damage function incorporating the stock component of the pollution in the objective function. Hence in the absence of a binding constraint on the stock of pollutant, the opportunity cost of the pollutant stock is not so high. But when (4) becomes binding the value of the co-state variableΛ_t captures theopportunity cost of the pollutant exceeding a certain optimum level. The marginal social cost of the damage due to the pollutant building up in the water is not known and this prevents an analysis based upon an agricultural-municipal tradeoff in the decision to use excess fertilizer. The issue of imposing tax rates on the application of the polluting input then emerges as a feasible alternative over trying to abate the stock of the pollutant. A detailed discussion on these appears in the empirical results in Chapter V.

<u>Some policy implications</u>

$$\dot{\lambda}_t = r\lambda_t + C'_t(S_t)N_t x_t$$

The above relationship describes the rate of change of the shadow price of the stock of water or the opportunity cost of drawing more water for present use.

Two observations may be made about the rate of change in λ_t:

If the discount rate is positive it serves as a compensation for delayed benefits (Hellegers et al., 2006). Also there is the extraction cost effect where larger stocks reduce extraction cost or smaller resource stock increases extraction cost. Then the following possibilities arise:

Assume that the initial stock of water is relatively large. The extraction cost may be very small because a marginal change in the stock of water is unlikely to cause a substantial change in the unit pumping costs. In this case $\dot{\lambda_t} = r$ or λ_t grows at rate of discount. Next we assume that the initial stock of water is small such that extraction cost effect is stronger than the discount rate effect. The shadow price of the stock of water declines over time.

In summary this chapter introduces a conceptual framework of the dynamic behavior of groundwater stock and the amount of pollutant using a continuous time optimal control framework. The joint application of irrigation water and nitrogen fertilizer affects the net benefit function but each input has a different impact on the marginal condition that holds for each farmer using them for growing crops. This is because of the social or external cost that the use of each input imposes on the time path of extraction and pollution. The time path of the co-state variables or the shadow prices for the stock of water and the stock of pollution capture the inter temporal changes in this external cost. The shadow price of the stock of groundwater can be decomposed into a scarcity effect and a cost savings effect where the scarcity effect arises from the marginal value imposed on the remaining reserve or stock of water due to the use of the water at any given period within the time horizon, and the cost effect comes from the cost savings due to lower water extraction now. In a depletable aquifer model both these effects can exist simultaneously. The time path for the shadow price of the stock of pollution follows the Hotelling rule whenever the pollution constraint is not binding. In the case where the stock of pollutant hits the maximum limit, the co-state variable may again be decomposed into a cost effect and a pollution abundance effect. While the cost effect is the reduction in pollution that may be achieved over time by applying less of the polluting input at any particular time, the effect of the stock of pollution accumulated that has a negative effect on the terminal value of the pollution stock is captured by the pollution abundance effect. The role of these state and co-state variables and their relationships over a twenty year planning horizon are discussed in the following chapters on empirical methodology and results.

CHAPTER IV

DATA AND METHODOLOGY

Study region

The Southern High Plains (SHP) of Texas is a highly researched area on groundwater withdrawals with all studies concluding the need for groundwater conservation and management. Though the rise in energy cost of pumping, fall in crop prices, and use of more efficient irrigation techniques have reduced withdrawals and even helped to minimize stabilize in certain regions, counties like Lynn, Hockley, Lubbock, and Terry continue to experience declining well depths. Aggravating the problem is the pollution of groundwater in these regions. With almost 95% of the aquifer used for irrigation purposes, application of nitrogen fertilizers contributes to high levels of nitrate concentration in wells across these counties. A series of recent USGS reports and two important studies by Hudak (2000) on nitrate levels confirm the presence of nitrate in Texas groundwater. According to Gurdak and Qi (2006), the probability of finding groundwater nitrate in the Southern High Plains is very high, the main source being fertilizers from irrigated cropland above the water. Going by ions formed after nitrogen decomposition, Reedy et al. (2007) concluded that counties like Lynn, Terry, and Lubbock have places in the aquifer that have nitrate concentrations as high as 14 mg/l, making them completely unusable for consumption. In their view, nitrate loads to the aquifer could increase in the future as natural nitrate deposits mobilized by irrigation return flow eventually reach the water table. These reports, though comprehensive in terms of laying out the foundations needed for a hydrological assessment of the situation, have very few suggestions for an economic solution to the problem.

This study will concentrate on two particular counties in an eight-county region in West Texas. All counties of the study region come under the High Plains Underground Water Conservation District (HPUWCD) no.1 and Groundwater Management Area 2 of the Texas Water Development Board (TWDB). Agricultural production is a dominant activity in all these counties, with cotton being the predominant crop grown in Lubbock and the counties south of it. Apart from Lamb, Lubbock, and Terry, which have used surface water in addition to groundwater in recent years, all these counties completely depend upon groundwater for irrigation.[13] Four main crops grown using sprinkler irrigation viz. corn, cotton, wheat and sorghum are considered for this study. On average, these counties together have produced 45,000 bushels of winter wheat, 67,000 bushels of sorghum, and 745,000 pounds of cotton annually during the period 1995-2008 (NASS) using groundwater from the Ogallala solely for their source of irrigation**.** While Castro has been the leading county in terms of groundwater use (382,000 acre-feet in the years 1987-08) in recent years, closely followed by Bailey and Lamb, unmanaged extraction has led to a situation where Lubbock and Lynn have resorted to surface water irrigation in recent years[14]. Given that the saturated thickness of the aquifer is going down in most of these counties, the almost complete dependence on groundwater has also prompted the HPUWCD to take up water conservation policies apart from the progression to advanced irrigation techniques by farmers.

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[13] According to Hudak (2000),72% of groundwater is used for irrigation statewide while the rest is divided between private/municipal use and for livestock, mining, and manufacturing.
[14] 2007 Water Use Survey Summary Estimates by TWDB.

The concern with nitrate pollution of the water is related to the overwhelming use of chemical fertilizers, especially inorganic nitrogen and anhydrous ammonia. In recent years, animal feedlot operations have also been a source of nitrate contamination of groundwater in Castro and Parmer. According to various TWDB reports on water quality in these counties, average nitrate concentration of groundwater in counties like Lubbock, Lynn, and Terry far exceed the drinking water limit (as evident from wells sampled in this region over the years 1955 to 2008), let alone their problem with water availability.[15]

The pollution problem however, is county specific in nature. In counties like Castro, Parmer, and Bailey, the problem is divided between agricultural activities and animal feedlot operations. The predominant nature of the soil is of the clay type where surface application of nitrogen fertilizer in irrigated cropland does not allow too much percolation below the soil because the clay particles are able to hold the chemical in their tight pores. Thus the nitrate pollution problem is not as acute as in the southern counties like Lubbock, Lynn, Hockley, Terry, and to some extent Lamb county to the east. These counties mostly grow cotton; the average amount of harvested acres for irrigated cotton in each of these counties exceeds 100,000 with the exception of Hockley. Two main factors are responsible for the high amounts of nitrate pollution from irrigated croplands in these counties. One, the dominant soil in these counties is sandy in texture and the most important crop of the region — cotton, is grown on this soil. The percolation of nitrogen below the vadose zone is more common here since sand facilitates the leaching of nutrients from the root zone. Secondly, as per the USGS Report (2007), pumping of groundwater for irrigation is a major facilitator for the movement of chemical

[15] From TWDB sources, the average level of nitrate concentration in the wells in the counties of Hockley, Lynn, Terry, and Lubbock are calculated as 13.27mg/l, 46.0405mg/l, 33.018mg/l, and 19.9097mg/l, respectively.

constituents from near the water table to deeper zones more rapidly. This is particularly true for the four counties above where continued irrigation practices have depleted the groundwater reserves to such an extent that corn irrigation has been abandoned almost completely in Lynn and Terry. The magnitude of nitrate pollution in these counties is borne out by the fact that over 90% of wells sampled here show nitrate concentration levels above or close to 10mg/l which is the EPA limit.

The main purpose of the study is to empirically investigate the joint management of groundwater quantity and quality for the above counties and prescribe policy instruments for two of those. Dryland or non-irrigated farming is not considered here, however and the whole focus of the study is on irrigated water use and fertilizer use and how policies for economic use of these two resources are likely to improve the present situation.

Optimization model

The study uses a 20 year dynamic optimization model to assess the economic tradeoff between water use and fertilizer use after accounting for the stock of water and pollutant every year. The dynamic optimization modeling in short, serves to maximize the discounted net revenues over a planning horizon subject to certain economic and hydrologic constraints. According to the Oklahoma Groundwater Law (1972), an aquifer should not be mined or should have a finite source of water in economic terms, at least within a twenty year period. Though Texas has the rule of capture in place, this medium term time horizon is selected to ensure that the depletable aquifer is not mined.

The initial model specification assumes that the level of aggregation is at the county level and all variables and parameters are defined in terms of an acre. The county level aggregation is often regarded as an approximation as it fails to account for spatial differences in hydrological, soil and even economic characteristics. However, the aim of this study is to solve for optimal values of the main control variables and examine their potential impact on the stock of water and the pollutant stock across the county. Hence aggregation at the county and crop level seems reasonable with some due limitations.

Let index *k* represent the crop and *t* represent the time horizon, which is typically a year. The inputs explicitly modeled in the production function are irrigation water and nitrogen fertilizer applied to crops. The price of each crop (P_{kt}) as well as the cost of a unit of nitrogen fertilizer applied (P_{mt}) is assumed to be fixed.

The crop production function is stated as:

$$y_{kt} = f_{kt}(x_{kt}, m_{kt})$$

where y_{kt} represents yield per acre of crop *k* at period *t*, x_{kt} represents the amount of irrigation water applied per acre for the crop in period *t*, and m_{kt} denotes the amount of nitrogen fertilizer applied per acre for the same. The production function satisfies the usual concavity conditions, $\frac{\delta y_{kt}}{\delta x_{kt}} > 0$, $\frac{\delta y_{kt}}{\delta m_{kt}} > 0$, and $\frac{\delta^2 y_{kt}}{\delta {x_{kt}}^2} < 0$, $\frac{\delta^2 y_{kt}}{\delta {m_{kt}}^2} < 0$ implying that both water and nitrogen are normal inputs showing diminishing marginal productivities. Also, joint complementarity between the use of these inputs is captured by $\frac{\delta}{\delta x_{kt}}\left(\frac{\delta y_{kt}}{\delta m_{kt}}\right) > 0$.

The optimal set of decisions is found by solving a joint-maximization model with the decision-making horizon for this problem being of length *T*. The discount factor in period *t* is defined as $\beta^t = (1 + r)^{-t}$ where *r* is an appropriately chosen interest rate. The dynamic optimization model assumes the following form:

$$Max \sum_{t=0}^{T-1} [\beta^t \sum_{k=1}^{K} \{P_{kt} f_{kt}(x_{kt}, m_{kt}) - P_{mt} m_{kt}\} - C_t(X_t) x_t] \quad (4.1)$$

subject to:

$$X_{(t+1)} = X_t + \left[(1-\alpha)\sum_{k=1}^{K} x_{kt} - R\right]/AS \quad (4.2)$$

$$(t = 0, \ldots \ldots . T-1)$$

$$ST_{(t+1)} = ST_t - \left[(1-\alpha)\sum_{k=1}^{K} x_{kt} - R\right]/AS \quad (4.3)$$
$$(t = 0, \ldots \ldots . T-1)$$

$$M_{(t+1)} = \eta l_t + (1-\delta) M_t \quad (4.4)$$

$$\sum_{k=1}^{K} x_{kt} \leq GPC_t(X_t) \quad (4.5)$$

$$S_T > 0, \qquad \mathrm{t = T} \quad (4.6)$$

The model objective function is given by equation (4.1) and consists of the following components. Let P_{kt} represent the exogenous price for crop *k* in year *t*. The first term represents gross revenues from all cropping activities in all years of the decision-making horizon. Let P_{mt} denote the exogenous price of nitrogen fertilizer in period *t*. The second expression in equation (4.1) represents the total cost of nitrogen fertilizer used for all crops produced over the decision-making horizon.

The last term in equation (4.1) represents the pumping cost of water where X_t refers to the average depth to water for the aquifer (pumping lift) in period *t*. Suppose C_t (X_t) is the marginal cost of withdrawing a unit of groundwater as a function of the pumping lift of the aquifer. Usually $C_t^{'}(X_t)$is assumed to be positive because a greater depth to groundwater (higher pumping lift in hydrological terms) leads to an increase in the marginal pumping cost. It is also assumed that $C_t^{''}(X_t) > 0$.

The constraint set for the dynamic optimization model is represented by the equations (4.2) – (4.5). Following convention, two state equations are incorporated to track the movement of the stock of water as it is pumped from the aquifer in any period *t*. The aquifer model formulation is similar to that found in Das et al. (2010) and Wheeler (2008) with the concept similar to Gisser (1983) and Gisser and Sanchez (1980). Equation (4.2) represents the change in the pumping lift of the aquifer where X_t is the pumping lift of the aquifer at time *t*, α (0 < α < 1) is the constant fraction of irrigation water applied in each period that constitutes return flow, *R* is the exogenous average recharge for the aquifer, *S* denotes the specific yield of the aquifer, and *A* is the land area overlying the Ogallala aquifer in Castro Country. (The return flow from irrigation as well as the exogenous return flow is assumed to be very low in the actual model). The saturated thickness of the aquifer in each time period ST_t is given by equation (4.3). The remaining parameters are as previously defined in equation (4.2).

The pollution of groundwater is not an instantaneous phenomenon. First, a fraction of the NO_3-N fertilizer actually leaches into the groundwater as runoff. A portion of this accumulated nitrate then undergoes degradation, which contributes to the pollution of groundwater. There is thus a delayed impact on the water from the time the fertilizer enters the ground to the point where it decomposes into a harmful chemical. The transportation and eventual decomposition of the chemical is a complex process determined by the nature of the soil, the depth into the aquifer where the chemical concentration is measured, the saturated thickness of the aquifer as well as a host of other factors.

The dynamic equation for the accumulation of nitrates M_t in the groundwater stock is given by equation (4.4) in the model constraint set. The specification of this equation recognizes that there is a difference between fertilizer applied on the surface and the proportion that percolates below the soil surface or vadose zone. The latter is actually responsible for the leaching and eventual accumulation of nitrates in the aquifer and depends upon the depth of the aquifer and its porosity. The function $l_t(x_t, m_t; q)$represents the total amount of nitrogen fertilizer percolating beneath the vadose. Leaching is assumed to usually increase with increased applications of irrigation water and nitrogen fertilizer for all crops. The parameter q denotes exogenous factors such as rainfall, soil nitrogen, and grain yields in some cases. The parameter η is a scalar that is computed on the basis of the aquifer depth and porosity. The parameter δ is an exogenous decay rate for nitrates in the groundwater stock.

The component of the base model constraint, equation (4.5), is the gross pumping capacity constraint given the irrigation technology in period *t*. This constraint is introduced to restrict the total pumped per acre for producing all crops in a county to the pumping capacity of the aquifer in the county at a point of time and changes dynamically. (For the derivation of the gross pumping capacity constraint, refer to Appendix B5).

Finally, (4.6) represents a terminal value function for the stock of water. As discussed in detail in Chapter III, it allows for the possibility that the stock of groundwater adds value to the net benefit function (4.1) beyond the current decision making period. In (4.6) the saturated thickness is assumed to represent the water stock—

the equation $S_T > 0$ holding at t=T, confirms the fact that there exists a finite stock of water in the terminal period T.

Data sources

The study utilizes well information for each county obtained from the Texas Water Development Board (TWDB). The crop prices correspond to a five year average of Food and Agricultural Policy Research Institute (FAPRI) prices while price of nitrogen fertilizer is taken from the Texas Crop and Livestock Enterprise Budget for 2011 (Texas A&M). The hydrologic parameters like specific yield and the initial values for saturated thickness and pumping lift of the aquifer are taken from 2008 estimates published by the Center for Geospatial Technology at Texas Tech while the economic parameters like the pump efficiency, energy price and the operating pressure of the pumping system have been borrowed from the figures in Wheeler (2008). The non pumping costs like the maintenance cost per acre for the irrigation system, irrigation labor cost per acre other fixed costs and harvest cost per acre are calculated from the projections obtained from the Texas Crop Enterprise Budget for 2011.[16] Data for irrigated acres for the four crops from 1968-2009 are obtained from the National Agricultural Statistics Service (NASS). The prices of the crops and price of nitrogen fertilizer, the price of electricity, the non pumping costs per acre and the values of the various hydrological parameters used are given in Appendix B1.

[16] It should be mentioned here that these projected figures change and might affect the actual values in the results though not having any impact on the conclusions. However the projected figures from 2010 and 2011 budget sheets were found to be very similar.

The main data sources for county-level fertilizer application levels for each crop are USGS and NASS, while the main data source for irrigation application levels is the Irrigation Water Use Estimates from TWDB.

Irrigation Data

The data for irrigation water use estimates for each crop in acre-feet.in each county are available from the TWDB Website from 1985-2008 and through email correspondence with Cameron Turner at TWDB**.** Total use can be divided by the number of irrigated acres to arrive at use of groundwater in feet per acre for the each crop in each county. This provides the total level of groundwater use in feet— if we multiply by 12 we get the amount of groundwater application in irrigated acres in inches.

Fertilizer Data

Data for fertilizer application comes from the nitrogen fertilizer use estimates for major crops as documented in the Lubbock Experimental Station. Also the default rates of fertilizer application for each crop as given in CRopman / EPIC is utilized during the actual simulations as described in the empirical methodology below.

Data to Estimate Initial Nitrate Concentration Level

The data for estimating the concentration level of nitrate is available for wells sampled over each county for a period of years starting from 1938 to 1955 an ending at 2007-08. These consist of irrigation and municipal wells and are representative of wells throughout the county. The TWDB database for wells contains information on well depth, years sampled, and location given by latitude and longitude. Since time of residence in the water, location of the wells sampled, and depth of the water table are important factors that determine the magnitude of possible nitrate pollution, these are considered as exogenous variables while estimating an initial concentration level of the nitrate.

Empirical Methodology

The study utilizes simulated data obtained from CRopman (Gerrick et.al. 2003) to estimate crop response functions and nitrogen leaching equations in the absence of actual data on nitrogen percolation. Two main procedures are followed in the empirical development of the model. First, CRopman is used to simulate crop yields and nitrate leaching through the vadose zone with each simulation conducted for a 40 year period starting from 1960 and ending in 1999. The simulations are done under the following specifications: reduced/conservation tillage, center pivot irrigation with 90% efficiency and a field size of 640 acres (this corresponds to the conventional definition of a field section in agriculture though CRopman generates crop yield on a per acre basis). For the soil structure the predominant soil type for growing crops in each county is considered based on data from NASS soil cover statistics. Due to lack of actual weather data the program uses the monthly average values to generate weather data. During each simulation, the amount of irrigation water and nitrogen levels are varied at nine to ten levels keeping soil, land conditions, irrigation system and various other parameters constant. While changing the quantities of the two primary inputs the relevant application rates per acre based on the estimates outlined above are taken into consideration. The irrigation timing is matched with planting and harvesting dates for crops in each county as obtained through email correspondence with Dr. Calvin Trostle[17] at Texas A&M University. The final outputs are compiled taking into account the variables —irrigation

[17]Extension Agronomist, Texas Agricultural Research Station, Texas A&M University.

and nitrogen for the crop response relationship and percolation below the root zone, grain yield, soil nitrogen, irrigation water, applied and growing season precipitation for estimation of the nitrogen percolation function .The annual average grain yield per acre is then regressed on irrigation water and nitrogen fertilizer applied for generating crop response functions, assuming different technological relationships between nitrogen and water. Leaching functions are estimated with mineral nitrogen loss as percolate as the dependent variable and percolation below the root zone, soil nitrogen, grain yield, growing season precipitation, irrigation and nitrogen applied as the independent variables.

The crop response and the leaching functions are estimated through both linear and nonlinear functional forms. The statistical relationships between yield as the dependent variable and irrigation water and nitrogen as the independent variables can be described by the following equations:

$$Y_i = \alpha_i + \beta_i IR + \gamma_i N + \varepsilon_i \qquad (4.7)$$

$$Y_i = \alpha_i + \beta_i IR + \gamma_i N + \delta_i IR^2 + \pi_i N^2 + \rho_i IR * N + \varepsilon_i \qquad (4.8)$$

$$Y_i = \alpha_i + \beta_i IR + \gamma_i N + \delta_i IR^{1/2} + \pi_i N^{1/2} + \rho_i \ (IR * N)^{1/2} + \varepsilon_i \qquad (4.9)$$

$$Y_i = \alpha_i + \beta_i IR * N + \gamma_i \ (IR * N)^2 + \varepsilon_i \qquad (4.10)$$

where, Y_i refers to the output of the ith crop per acre, IR and N are the irrigation water and fertilizer applied per acre for growing the crop, $\beta_i \gamma_i \delta_i \pi_i$ and $\rho_i$are slope parameters and$\varepsilon_i$is the random error term.

The nitrogen leaching equations used have three variations- linear, exponential and Tobit. The choice of Tobit is guided by the fact that the dependent variable which is nitrogen loss in percolate assumes a value of zero in many years of the simulations. Five main independent variables viz. percolation below the root zone, soil nitrogen, irrigation water, nitrogen fertilizer and grain yield are taken as influencing the amount of nitrogen leached below the root zone. Selection of these variables was contingent upon theory as well as upon the high correlation with the dependent variable as evident from crop and county specific simulated data. A level of irrigation water applied may have an impact on plant uptake of fertilizer and hence nitrogen leached. Soil N_2 and rainfall together or the latter individually, may contribute to leaching. Percolation below the root zone is correlated with the loss of mineral nitrogen as percolate. Sometimes the quantity of grain yield can influence the amount of nitrogen leached beneath the root zone as was the case for cotton though it hardly matters for corn. Equations (4.11)-(4.13) describe the technical relationships between leaching of mineral nitrogen as the dependent variable and the main independent variables.

$$NL_i = \alpha_i + \beta_i PRK + \vartheta_i GYLD + \gamma_i TNO3 + \delta_i IR + \pi_i N + \varepsilon_i \tag{4.11}$$

$$NL_i = \alpha_i + \beta_i PRK + \tau_i PREC + \gamma_i GYLD + \delta_i TNO3 + \pi_i IR + \rho_i N + \varepsilon_i \tag{4.12}$$

$$NL_i = exp[\alpha_i + \beta_i GYLD + \tau_i (IR * N) + \gamma_i PRK + \delta_i TNO3 + \pi_i IR + \rho_i N + \varphi_i (IR * TNO3) + \varepsilon_i] \tag{4.13}$$

(4.12) is estimated for a linear version as well as for a Tobit specification. Here NL_i refers to the quantity of mineral nitrogen loss in percolate per acre from the production of the crop, PRK is the percolation of fertilizer below the root zone, $TNO3$ denotes the nitrogen associated with the soil and IR and N are as defined above. (4.13) is a nonlinear version which includes grain yield and the two interaction terms - irrigation with applied nitrogen and irrigation with soil nitrogen to capture possible variations in leaching that can be explained by the interaction between irrigation water and nitrogen that is already present in the soil during crop production. [18]

Estimation results

Tables B6.1 to B6.14 in the appendix B6 show the estimates for the different types of functional form specifications for Castro County and for Lubbock County in West Texas. Crop specific estimations are done for Bailey, Lubbock, Lynn and Castro and the estimates from the production functions and the leaching functions are used for the neighboring county with the same soil type and irrigation practices. The estimates from the quadratic functional form in (4.10) are considered for the production function for cotton, wheat and sorghum, while for corn the convergence is attained best with functional form (4.8). The selection of the functional form (4.10) follows from the fact that in the actual simulations irrigation water and fertilizer were varied in proportion to each other as complementary inputs in crop production. This often leads to a high degree of collinearity which is taken care of by introducing the interaction terms. Tables B6.1-B6.4 shows the crop response for Castro County. As mentioned above the quadratic specification worked best for corn, with the interaction term having an estimated effect of 0.02 on the yield of corn. For the specification with just the interaction between the two inputs, there is a 7% increase in the yield of corn due the joint application of nitrogen and

[18]The nonlinear leaching estimates from (4.13) did not converge for all crops when tried in SAS and hence the estimates are not reported here.

water. For wheat and grain sorghum, the joint application of the two inputs lead to a respective increase of 0.06% and 5% in the yields while for cotton a unit increase in applied water and nitrogen leads to a 0.79 lbs. increase in the yield per acre.

For the nitrogen leaching equations, those from the Tobit specification in (4.12) are mainly used because of the reasons mentioned above. However least squares estimation is employed in cases where the percolate observations do not assume a value of zero in the simulated data. The estimates for the nitrogen percolate are discussed with reference to Tables B6.5-B6.8 for Castro County. The linear and the Tobit estimates for percolate are almost similar in the signs and significance but for corn and cotton, the Tobit estimates are preferred due to the dependent variable assuming a value of zero during several years. PRK (percolation below the root zone) as expected is always positively correlated with nitrogen percolate and for cotton one pound of percolation amounts to actually to 31.18lbs increase in the percolate. Interestingly for cotton, one pound increase in yield actually raises the nitrogen percolate by 12% unlike all the other crops. High yields are often associated with high levels of residual nitrogen resulting in greater probability of loss as percolate. Except for grain sorghum, increase in irrigation water applied affects the percolate loss negatively (the coefficients are all statistically significant at 1%) probably accounting for the fact that irrigation water contributes to higher yield and hence reduces the loss in nitrogen. It should be noted that the estimated coefficients for the independent variables are all significant at 5% level at least for all the crops except corn.

For Lubbock County, the estimates for the crop response and leaching equations are laid out in Tables B6.9-B6.14. Of all the three crops considered in this region, cotton seems to be the most responsive to the joint application of irrigation water and nitrogen fertilizer, with the interaction term affecting the yield of cotton by 17% per acre. In contrast, for sorghum and wheat, the yields increase by 5% and 2% respectively as evident from the estimated coefficients for the interaction term. Turning to the leaching equations, the Tobit functional form is used for sorghum and cotton while the linear functional form is used for wheat. Except for the wheat leaching equation, the effects of the parameters responsible for leaching are somewhat different from those for Castro County. For instance, nitrogen applied is found to affect the nitrogen loss as percolate negatively for grain sorghum and cotton while nitrogen already present in the soil affects the former positively. A possible reason might be that the predominantly sandy nature of the soil in Lubbock facilitates the percolation of nitrogen that is left after application while sorghum and cotton both absorb whatever is applied. Though the estimated coefficients are significant at 5%, the magnitudes are low implying that both soil nitrogen and nitrogen applied have small impacts on percolation. For all three crops growing season precipitation affects nitrogen leaching negatively. Higher yield and higher levels of irrigation water lead to higher loss in nitrogen percolate with an inch of additional irrigation water amounting to around 6 lbs loss in mineral nitrogen for sorghum. For wheat one pound of applied nitrogen leads to a 3 pound loss of percolate while other factors like precipitation, yield, soil nitrogen and irrigation water seem to be affecting the nitrogen loss negatively.

The pollution stock

Next follow the nitrate concentration relationships for each county. The nitrate pollution equation of motion closely follows the relationship used previously by Anderson et al.

(1985),Conrad and Olson (1992), Yadav (1997), Nkonya and Featherstone (2000), Roseta-Palma (2002, 2003), and several other resource economists in recent years.

$$M_{i(t+1)} = \sum_{k=1}^{K} \sum_{\theta=1}^{t} (1-\gamma) m_{i\theta} + (1-\delta) M_{it} \tag{4.14}$$

where M_{it} refers to the built up or initial value for nitrate concentration for the ith county as obtained from the equation above.

In their study on Aldicarb application on potato fields and its effect on groundwater quality in Rhode Island, Anderson et al. (1985) came up with a state equation as above with the assumption that surface-level application of Aldicarb and its transformation into a pollutant depend on certain well characteristics such as the depth, distance at which the Aldicarb is applied, and soil characteristics at the application site. In their empirical demonstration, they took the Aldicarb application and converted it into a well concentration level by multiplying the application with what they call a “decay adjusted coefficient.” This term was estimated by regressing the application rate on well depth and distance from the well, which were basically the factors responsible for converting the actual application of Aldicarb in pounds to mg/l. Then a decay corrected application was calculated by considering days of decay in the groundwater along with the pesticide decay when applied in the first year. Eventually the concentration level was measured as a function of the depth of the well(s) and distance from the well at which the Aldicarb was applied, all multiplied by the decay corrected application.

Conrad and Olson (1992) used a similar dynamic relationship to analyze the consequences of putting the New York health standard of 7ppb as the MCL on the application of Aldicarb on potato fields. They first found an analytical solution for the steady-state values of social welfare and concentration level, with the latter being a function of the Aldicarb application rate, also at the steady state. Next employing Aldicarb application data from 1970 to 1979, they generated simulated concentrations of Aldicarb for 1975-2000, applying an estimate of the decay rate they derived using past pollution data. This constitutes their version of $M_{i(t+1)}$. Then they regressed actual concentration data on simulated concentrations to arrive at an estimate of the decay rate δ. Their base solutions for the level of output and Aldicarb concentration considered the profit maximizing rate of Aldicarb application, which was higher than that at the steady state. But with the health standard concentration level, the rate of application of Aldicarb was smaller and there was also an accompanying cost or damage coefficient for the concentration.

Yadav (1997) followed the Conrad and Olson procedure of deriving steady-state solutions of nitrogen application as a function of the nitrate concentration level. Selecting three contamination sites, he calculated the steady-state values of nitrogen application rates under the steady-state concentrations at the EPA standard of 10mg/l using the dynamic equation (4.14) above (Yadav, pp. 938- 941). His results on optimum nitrogen application rates were based on experimental parameters that convert the nitrate concentration levels in mg/l to nitrogen application figures in lbs. /acre. The underlying assumption was that the nitrate concentrations below the root zone, the source of which was the leaching of fertilizer applied, is representative of nitrate concentrations in the underlying aquifer.

Nkonya and Featherstone (2000) applied a similar dynamic relationship, but unlike Conrad and Olson or Yadav, they actually estimated the pollution transition equation by ordinary least squares using soil profile nitrate data. The results with the estimated parameters were put into a nitrate-constrained profit maximization problem and an unconstrained problem to compare the differences in net profits. Their methodology, though straightforward, is based on experimental data like Yadav and was dependent upon a site-specific soil profile relationship to recover the estimates from the dynamic equation of motion.

Roseta-Palma (2003), however, had a different approach in the estimation of $M_{i(t+1)}$. She developed a hypothetical management scenario of a contaminated aquifer using estimated parameters borrowed from the literature. The state equation of motion in her formulation took the form

$$M_{i(t+1)} = \eta NO_3 - \delta M_{it}$$

where NO_3 is the nitrate leaching function estimated as $NO_3 = h + i\gamma + jg + k\gamma g$ (h, i, j and $k$being coefficients and γ and g are the amounts of nitrogen fertilizer applied and irrigation water extracted*)* .The idea was to solve for the steady-state value for M and starts out with some initial (base) level of M_{it} for each county. This approach for estimating just the leaching function directly and using it in the main equation of motion is less complicated in its derivation and use than the estimation procedures detailed above. However, this assumes nitrate leaching strictly as a function of the two main inputs into crop production and thus is almost similar to obtaining a nitrogen application rate. In addition, it also abstains from starting out with an estimated value for concentration of nitrate for an individual county (M_{it}) based on parameters that considered to be among factors responsible for the nitrate stock in water.[19] Instead it uses parameters borrowed from earlier work to conform to theory. Last but not the least, the

[19] USGS Scientific Investigations Report by Gurdak and Qi (2006).

data for actual nitrogen leaching into the vadose zone is impossible to come by without utilizing some simulation technique to generate leaching observations for nitrogen for each crop in each county.

From the description of the various techniques above, it is clear that the dynamic interrelationship between nitrogen application as a flow variable and the concentration of nitrate as a stock in groundwater needs to be modeled carefully given site-specific data and reliable parameter estimates. The concentration level is modeled as a function of the three most important independent variables that are believed to affect the level of pollution concentration inside an aquifer – its location, the depth, and year of observation. Since data is available from the Texas Water Development Board (TWDB) on individual wells in a county, the concentration of nitrate in the county is estimated by considering all wells together, including public drinking water wells. First, the county is divided into geographic grids by location specific parameters like rows and columns with the help of Arc GIS. These are taken as location dummies for the wells while well depth and the year of measurement are obtained from the TWDB well database for each county. (For most counties, these wells have been measured multiple times over the entire time period, while some wells have been tested once or twice for the level of nitrate concentration). Thus, a cross sectional regression (see equation (4.15) below) of concentration level on the main independent variables mentioned above is carried out using either ordinary least squares or weighted least squares with well depths as weights for some counties

$$M_{it} = \gamma_0 + \gamma_1 row + \gamma_2 col + \gamma_3 depth + \gamma_4 year + \varepsilon_t \qquad (4.15)$$

The variable M_{it} is an approximation for the initial nitrate level or the nitrate concentration already built up within the aquifer over the years in the ith county (initial in an empirical sense means if we start out at time t_0). The estimated nitrate levels are found to correspond to the average nitrate levels in the wells over the sampling period through a paired t-test as well as through comparison of their statistical distributions.

The above methodology to derive the dynamic equation of motion resembles the ones used by Yadav (1997) and Nkonya and Featherstone (2000) but differs slightly in the treatment of the nitrogen application level. While both these authors consider a delayed relationship between the time of application and the time when it contributes to the nitrate concentration, here it is postulated that there is a starting time period t_0 and a finite horizon between t=1 and t=T-1 when the fertilizer is applied which might contribute to nitrate pollution later.

Calculation of irrigated land

Historical estimates of irrigated acres for the crops in each county as provided by NASS are used to arrive at figures for irrigated acres in total for each county for the dynamic simulation covering 20 years. Projected irrigated acreage per county for the four crops is derived by taking a trend of the actual data. Usually two methods are employed to obtain future projections based on historical data. First, projections are derived through historical data+/- estimated trend (regression of the irrigated acres on years).The irrigated acres obtained through this method did not fit well with the past observations. So, the following approach is adopted. Based on past data from 1973-2008, a trend for future irrigated acreage is obtained which is used to derive approximate values for the same.

Pumping cost

Finally, the marginal pumping cost C_t (X_t) is assumed to be a linear function of lift and is written as follows.

$$C_t(X_t) = \frac{EF * (X_t + 2.31 * PSI) * EP}{EFF} \tag{4.16}$$

where EF is the energy use factor for electricity, PSI is the system operating pressure, EP is the energy price, and EFF is the pump engine efficiency. These definitions and their respective values are drawn largely from Wheeler (2008) and from Das et al. (2010).

CHAPTER V

RESULTS AND DISCUSSIONS

The main objective of this research is to make an empirical assessment of the economic tradeoff involved in the production of agricultural crops using irrigation water and nitrogen fertilizer as inputs against the attending costs of serious groundwater pollution in the long run. To this end, it captures the dynamic behavior of the stock of groundwater as well as the stock of pollutant over a twenty year period. This chapter identifies a baseline solution for the counties of Castro and Lubbock by maximizing the discounted net benefit per acre with constraints faced in the quantity and quality of groundwater. In addition, suitable management strategies through economic policy instruments such as input use restrictions, buyout policy and restriction on the stock of water remaining at the terminal period, are devised that can help to reach at least a ‘second best’ solution for groundwater withdrawal and fertilizer application.

The results shown here are based on irrigated agriculture in these counties of West Texas. Though non irrigated production has been predominant in Lamb, Hockley, Lynn and Terry counties in recent years the main contribution of this study is to find out an economic impact of crop production using irrigation water from the Ogallala and nitrogen fertilizer as the two primary inputs and at the same time to investigate the extent to which this production affects the water stock and quality levels. Ogallala is the sole source of irrigation water for Castro County and Lubbock has been using a very small percentge of surface water for irrigation from the last decade.

Policies explored

The estimates from the crop response functions and the percolation equations from Chapter IV are used to derive a dynamic model for determining the optimal levels of nitrogen fertilizer and irrigation water used, having the stock of nitrate concentration and the height of the water table as the two equations of motion. While the mathematical purpose of the optimization is to maximize the net present value (NPV) of crop production over a twenty year planning horizon subject to the constraints (4.2) to (4.6) above, the economic objective is to assess the impact of water extraction and nitrogen use more from a policy perspective. The model is first solved for a base run to obtain the optimal values of irrigation, nitrogen fertilizer, nitrogen percolation below the root zone, pumping lift and saturated thickness of the aquifer, nitrate concentration in the groundwater, pumping cost of water and the net present value of production using a discount rate of 5% as commonly used in water quality studies.[20].Then, it is resolved by including a maximum constraint on the level of fertilizer applied per acre. With a constraint on the level of fertilizer applied at every period, a positive shadow price will be generated every time the constraint is binding. This shadow price is a proxy for a “tax” on the agent for any application of fertilizer beyond a definite limit that can potentially contribute to groundwater pollution. (In the pollution literature this is often referred to as a best management practice).As a contrast to this endogenously solved “tax rate”, the

[20]For a discussion on the discount rate, please refer to Nkonya and Featherstone (2000, pp. 459).

price of nitrogen fertilizer is successively raised to \$0.52/lb (5% increase) and to \$0.55/lb (10% increase). This may be thought of as an external tax on the fertilizer use.

Finally, a set of policies are proposed that take care of the joint management of the two main inputs. These are respectively a quota on the use of irrigation water per acre, a restriction on the terminal value for saturated thickness and a water rights buyout policy where an agent can sell her water rights over the time period under study to an external agency. The first two are targeted to restrict the use of water per acre for a direct impact on the stock of water at the end of the twenty year period. The buyout policy, on the other hand, offers a financial incentive on the agent to conserve water in the present period through selling her rights to groundwater over her land and later having the choice to reorient production to dry land or irrigated agriculture. The water rights buyout policy compensates the agent every year for using few inches of water less than the unrestricted base value. Empirically, this shows up in the objective function (4.1) as an added revenue component for the agent, something which comes from the regulatory agency. The purchase of water rights may take place through negotiations between agents and the High Plains Underground Water Conservation District (HPUWCD).This is in line with USDA's Conservation Reserve Program and has been followed in Wheeler (2008) for nineteen counties of Texas overlaying the Ogallala aquifer. The farmers have the choice to raise production through dry land farming. The buyout of water rights from the Government's perspective is an economic tradeoff between incurring expenditure for water conservation and higher irrigated production and revenues in the future. As pointed out, the idea is similar to the Conservation Reserve Program but differs in terms of implementation.

The purpose of this exercise is to examine the effect of each policy in terms of maintaining an economic and physical balance in the stock of water as well as in the stock of pollution and the long run impact on farmers' net revenues. The optimization models are solved using the price of corn at $3.89/ bushel, the price of sorghum at$3.47/bushel, the price of cotton at $0.56/lb., the price of wheat at $5.69/bushel and the price of nitrogen fertilizer at $0.50/lb.[21]

Castro County

Castro County base solution

The results for the base solutions and for the policy simulations are presented for two counties--Castro which lies towards the northern part of the study region and Lubbock which is more towards the southern part. Table C.1 in the Appendix C reports the solutions from the base model for Castro County. Total irrigation water used per acre declines by around 0.22% at the end of year twenty while the use of nitrogen fertilizer increases by 0.33%. The fall in the irrigation water use might be attributed to the fall in saturated thickness from 79 feet at the start of the initial period to 44 feet at the end, which also gets reflected in a pumping lift increase from 233feet to approximately 267 feet in year twenty. The base results demonstrate that due to the steady increase in the level of nitrogen percolation below the surface from 92.57lb/acre to 94.02lb/acre as a result of the unconstrained use of fertilizer per acre, the nitrate concentration picks up in the later years to more than 17mg/l, much above the EPA maximum concentration limit for drinking water standard which is 10mg/l.

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[21]The crop prices correspond to a five year average of FAPRI prices while the cost of nitrogen fertilizer is obtained from the Texas Crop Enterprise Budget Sheets.

Fertilizer price rise

The next two tables (C.2 and C.3) describe the effect of an increase in the price of the fertilizer. As can be seen from Table C.2, with a 5% rise in fertilizer price, the discounted net revenue per acre falls by $28.76 from the base value, and the nitrate concentration in groundwater goes up to 16.27mg/l at the end of year twenty, which is just 0.79mg/l short of the corresponding base value. A possible reason might be the drop in the amount of nitrogen fertilizer percolating beneath the surface to 89.43 lbs/acre by year twenty. The change in saturated thickness and pumping lift is approximately the same as the base run change. With a 10% rise in the price of the fertilizer (Table C.3) there is a fall in the level of nitrates in groundwater to 15.77 mg/l and the loss in net present value as compared to the base run amounts to $102.32. In both cases of raising the price of the polluting input, it may be observed that the disincentive of using the input is marginal-for a 5% increase in price the use of fertilizer varies between 156.70-156.22lbs/acre while for a 10% rise it the application per acre ranges between 155.57lbs-156.08lbs. The base use of fertilizer on irrigated land is between 158.52lbs/acre to 159.05lbs/acre on average Thus there is evidence of a quantity/quality tradeoff in the use of groundwater though the increase in pumping lift and the fall in saturated thickness might have been slower if an option of switching to dry land production was present in the model. As mentioned in the section on empirical methodology, these changes in fertilizer prices represent an explicit cost on the use of fertilizer per acre and hence may be treated as an exogenous tax imposed on an agent for the use of fertilizer. Thus, from the above discussions, it may be inferred that a $0.03 tax on every pound of nitrogen bought is almost as effective in maintaining the groundwater quantity and quality as a $0.05 tax, even if the total fertilizer application per acre for growing crops differs initially after the respective price increases.

Fertilizer application limit

As an alternative to a direct increase in fertilizer prices, a kind of best management scenario is devised where the fertilizer use per acre is restricted to a certain limit. Restriction on the input use is similar to the standards and charges approach introduced by Baumol and Oates (1971). So violation of this standard raises the issue of imposition of a tax on the use of the input. The economically feasible limit for the county is selected to be in the range of 144-146lbs/acre of nitrogen applied by running several sensitivity tests to the initial application level. Beyond 146lbs/acre the concentration of nitrate and the percolation of nitrogen below the root zone increase consistently. On the other hand, a restriction on nitrogen applied to below 144lb/acre has a strong negative impact on the net revenues every year. Attention is restricted here to a fertilizer application level of 144lbs/acre which works best, *ceteris paribus*, in terms of its effect on the net revenue and also on the nitrate concentration, i.e. not a remarkable loss in net revenue with nitrate concentrations close to the EPA limit of 10mg/l. The results appear in Table C.4. The nitrate level is seen to fall to 10.36 mg/l and the percolation below the root zone falls drastically from 94.02lbs/acre in the base run to 54.96lbs/acre, which is a 40% decrease over the entire time period.. From the revenue perspective the imposition of this constraint has two implications-(a) the net present value differs slightly from the base level ($2.67 per acre loss in discounted revenue at year twenty) (b) the shadow prices which represent the opportunity cost of the constraint being binding at any period may act as an endogenously calculated tax rate on any application of nitrogen exceeding

144lbs/ace. As seen from Table C.4, it ranges from $0.34-$0.14/lb of excess fertilizer applied for the entire period. [22]

Quota on water use

Next economic policy instruments to conserve the stock of water as well as controlling the stock of pollutant are considered. The quota policy restricts the amount of irrigation water use by allowing agents to draw 0.50 acre inches less of water every year from the average use of 8.18 acre inches per acre in the base run. It is accompanied by the constraint on fertilizer use at 144 lbs./acre every year. The results are shown in Table C.5 in the Appendix C. The gain in the terminal level of water stock is around 2 feet from the base value and the nitrate stock falls by 2.82 mg/l on average at the end of year twenty. There is a loss in net present value of $241.34 per acre, which follows from a fall in net revenues even when the total cost including the cost of water withdrawal falls by around 9% in year twenty due to the restriction.

Restriction on saturated thickness

The restriction on the terminal value of saturated thickness to 50 feet is an alternative way to preserve the stock of groundwater for irrigated water use to more than 60 % of the initial reserve. The results are summarized in Table C.6 in the Appendix C. The notable impact is on the pumping cost which drops to an average of $4.85/acre inch from the average base value of $5.81/ acre inch-a consequence of reduced water use (average use is 6.90 acre inches/acre compared to base use of 8.18 acre inches/acre) and the fall in the

[22] A separate discussion by raising the fertilizer price by the amount of this shadow price by taking an average of the above opportunity costs over the years is not presented here.

terminal period pumping lift (which decreases by 5 feet from the base value) both of which directly affects the cost of water withdrawal. Though the impact on average increase in nitrate levels is smaller than the base value (13.71 mg/l at the end of the period), the loss in the NPV of production is a massive $872/acre. For the agent the revenue loss may be balanced by a corresponding gain in the amount of groundwater reserve. When saturated thickness is allowed to fall to 50 feet, it is equivalent to approximately 197264.7 acre feet of water conserved in terms of projected irrigated acres of land use over the entire time period. This may be interpreted as a long run water savings policy or a sustainable use of water at present.

Buying out water rights

The final policy is to evaluate the impact of a twenty year water rights buyout along with the previous restriction on the use of nitrogen fertilizer for Castro County. The important consideration here is the price to be paid to the agent for selling his water rights by 2 acre inches every year. For each year this price corresponds to the shadow price obtained from imposition of a water demand and supply constraint in the joint maximization problem. Thus the prices are exogenous and are found to vary between $0.15/ acre inch to $0.52/ acre inch. On average the irrigation water use is found to decline to 6.64 acre inches/acre while the saturated thickness level drops by 28.24 feet at the end of the time period, much lower than the base value of 34 feet (refer to Table C.7 in the Appendix C). This has a direct bearing upon the pumping cost which reduces to $4.66/ acre inch at the mean over the twenty years. The notable effects are on the discounted net revenues and the level of nitrate in the water. The nitrate stock increases by only 4 mg/l over the years. The agents also reap the maximum financial benefit from the buyout policy (the gain in NPV of production from the base level is $209.82/acre) as is seen from Table V-1below.

Table V.1: Change in discounted net revenues per acre over the twenty year planning period

years	base $/acre	nitp_0.53 $/acre	nitp_0.55 $/acre	constraint $/acre	quota $/acre	satt_50 $/acre	buyout $/acre
1	477.76	-4.47	-7.43	-1.75	-18.02	-43.85	14.07
2	477.31	-4.48	-7.44	-1.80	-17.96	-43.75	14.22
3	476.87	-4.48	-7.44	-1.85	-17.91	-43.64	14.37
4	476.44	-4.49	-7.45	-1.90	-17.86	-43.54	14.52
5	476.00	-4.49	-7.46	-1.95	-17.80	-43.44	14.67
6	475.57	-4.50	-7.47	-2.00	-17.75	-43.34	14.81
7	475.14	-4.50	-7.48	-2.05	-17.70	-43.25	14.96
8	474.71	-4.51	-7.48	-2.10	-17.65	-43.15	15.11
9	474.28	-4.51	-7.49	-2.14	-17.60	-43.05	15.25
10	473.86	-4.52	-7.50	-2.19	-17.55	-42.95	15.40
11	473.44	-4.52	-7.51	-2.24	-17.50	-42.86	15.54
12	473.02	-4.53	-7.52	-2.29	-17.45	-51.87	15.68
13	472.61	-4.53	-7.52	-2.34	-17.40	-63.74	15.82
14	472.20	-4.54	-7.53	-2.38	-17.35	-80.72	15.94
15	471.79	-4.54	-7.54	-2.43	-17.30	-99.20	16.01
16	471.39	-4.54	-7.55	-2.48	-17.25	-119.32	16.05
17	470.98	-4.55	-7.55	-2.52	-17.20	-147.17	16.09
18	470.58	-4.55	-7.56	-2.57	-17.16	-176.61	16.51
19	470.18	-4.56	-7.57	-2.62	-17.12	-208.67	17.07
20	469.78	-4.56	-7.58	-2.66	-17.08	-13.08	17.21

Note: *nitp_0.53* and *nitp_0.55* refer to price of fertilizer being raised by 5% and 10% respectively. *Constraint* refers to the limit on fertilizer application of 144lbs/acre. *Quota* denotes the restriction of irrigation water use by $0.50 per acre inch from the average base value. *Satt_50* refers to the saturated thickness being restricted to 50 feet at the end of the terminal period, while *buyout* denotes the purchase of water rights by around 2 acre inches per acre by the Groundwater Conservation District.

The buyout policy leads to an increase in discounted net revenues varying between $14.07 to $17.21 as compared to the base run, while as documented before, the negative impact on discounted net revenues is lowest for the policy where we impose a fertilizer use restriction of 144lbs/acre.

Table V.2and Figs.V.1and V.2below show the effect on saturated thickness and nitrate concentration over the twenty year time period.

Table V.2: **Change in saturated thickness over the twenty years for the base situation and the different policies**

Years	Base feet	Quota feet	satt_50 feet	Buyout feet
1	79.00	79.00	79.00	79.00
2	77.08	77.20	77.32	77.44
3	75.17	75.41	75.64	75.90
4	73.28	73.63	73.97	74.36
5	71.39	71.86	72.32	72.82
6	69.51	70.10	70.67	71.30
7	67.64	68.35	69.02	69.78
8	65.78	66.60	67.39	68.27
9	63.94	64.87	65.77	66.77
10	62.10	63.14	64.15	65.28
11	60.27	61.43	62.54	63.79
12	58.47	59.74	60.96	62.33
13	56.66	58.04	59.39	60.86
14	54.88	56.37	57.88	59.42
15	53.11	54.70	56.43	57.98
16	51.35	53.05	55.02	56.55
17	49.60	51.40	53.67	55.13
18	47.84	49.75	52.38	53.70
19	46.09	48.10	51.15	52.27
20	44.34	46.47	50.00	50.86

Note*: Quota* denotes the restriction of irrigation water use by $0.50 per acre inch from the average base value. *satt_50* refers to the saturated thickness being restricted to 50 feet at the end of the terminal period, while *buyout* denotes the purchase of water rights by around 2 acre inches per acre by the Groundwater Conservation District.

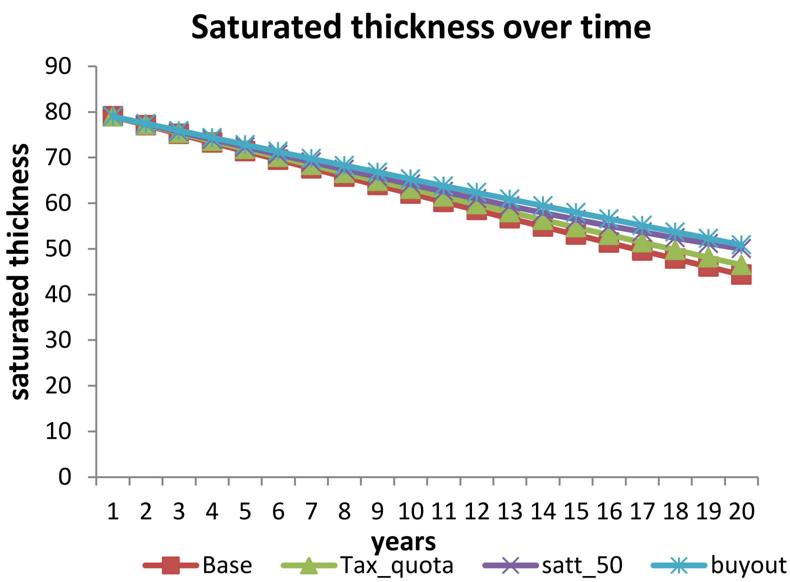

Fig.V.1: The time path of saturated thickness of the aquifer in the twenty year period for the base run and the different policies

Evidently, the fall in saturated thickness over time is lowest for the buyout policy but the dynamic time paths for the saturated thickness differ very little between the base level and when the quota on water use is imposed.

As far as the contribution to the pollutant stock is concerned, the buyout policy has the least impact too as is shown in Fig. V.2. As the figure describes, the policy of putting a constraint on the use of fertilizer alone has similar impact upon the accumulation of nitrate stock over time.

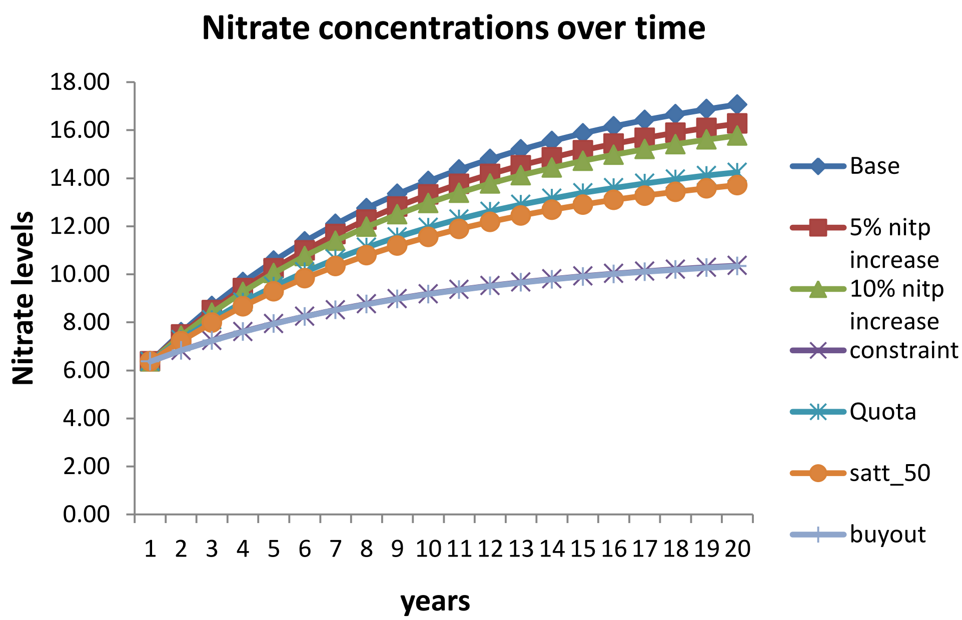

Fig.V.2: The time path of the nitrate level in the aquifer in the twenty year period for the base run and the different policies

What is apparent from the solutions above is that any external change in the fertilizer price has a marginal impact on the level of nitrate concentration over the time period, with a 10% rise in fertilizer price /lb. reducing the nitrate content at year twenty to a mere 5% from the base value. However the fall in net present value per acre to much above $50[23] for these percentage rises in prices may be an indication that an exogenously set price level for the fertilizer may cause net benefits to fall over time. The rise in fertilizer prices by 5%, and 10%, when looked upon as exogenous tax rates of $0.03 and $0.05 per pound of fertilizer used, is transparent and easier to implement by a regulatory authority. On the other hand there is the best management practice of restricting fertilizer application to 144 lb./acre. This policy is effective as far as the impact on water quality and net returns is concerned. However, the question remains on how to impose this tax on

[23]The net present value per acre is $6517 for the base run while for a 5% increase in fertilizer price per pound it amounts to $6455.62 per acre and to $6414.68 per acre for a 10% increase.

the agents considering that the shadow prices on the constraint set could serve as the tax rates over the time period. Although not apparent from the model solution, the endogenous tax rates may be applicable at definite time periods when the use of fertilizer attains the limit and the penalty as reflected in these shadow prices may not turn out to be sufficiently high to compel the agent to restrict his fertilizer use per acre. The policy maker's decision will thus have to be anchored on the benefits of maintaining the nitrate levels much below the EPA limits against the attendant costs of monitoring the fertilizer application every period.

In contrast, the policies that focus on the joint management of water quantity and quality, particularly the water buyout policy puts the onus on the agent to reduce her use of water throughout the planning period to achieve long term conservation of the reserves. The quota on water use and the policy of allowing the saturated thickness not to fall below 50 feet both have positive effects on the stock of water and the stock of pollutant relative to the base situation. However, the unfavorable impacts on the discounted net revenues is an indication that such policies may be hard to enforce by the HPUWCD under the present rule of capture and the traditional view of groundwater being common property. By and large, it remains an open question on how to best implement these policies unless a tax is imposed on water use above say, what is given by the optimization model. This tax rate may be calculated in the same way as the price of the water rights buyout. The buyout policy does not suffer from the above limitations. Moreover, like the policy of restricting fertilizer use level, it has a minimal effect upon the stock of nitrates over time. In fact, the water rights buyout enables the agent to gain on average $15.46 per acre in discounted revenues from the base value and leads to a fall in saturated thickness level to 28.24 feet at the end of the time period, much lower than the base value reduction of 34 feet in the level of water. So from policy perspective, this stands out as most effective as far the solutions from the optimization model are concerned.[24]

Lubbock County

Lubbock County base solution

Tables C.10 –C.17 describe the results for Lubbock County. The base results (given in Table C.10) show an initial irrigation water use of around 4 acre inches per acre for the twenty years and an initial fertilizer use of about 68 lbs/acre. The input use does not vary through the years. The fall in discounted net revenues is also very small (around $1.36 per acre) at the end of the planning period while the saturated thickness falls by around 21% from the initial year. However, the interesting impact is on the behavior of the nitrate concentration over time which falls from 21.02 mg/l to 14.76 mg/l in year twenty (assuming a 1% degradation rate of the percolated nitrogen once it reaches the aquifer). The fall in nitrate levels may be attributed to the lesser use of nitrogen fertilizer per acre which is a direct consequence of the southern counties shifting to dry land farming in recent years.

Fertilizer price rise

Next the fertilizer price is raised by 5%. The results appear in Table C.11. The NPV per acre falls by $26.66 from the base NPV and the discounted net revenue per acre go down

[24]For a complete comparison of the discounted net revenues and the pollutant stock under the different policies over time refer to Tables XVI and XVII in the appendix.

by $1.94 in the terminal period when compared to the same in the base run. The crop yields and input application rates as wells as the time path of the saturated thickness and the pumping lift remain the same as the base run. More or less the same results hold when the fertilizer price is raised to $0.55/acre (Table C.12 in the Appendix C), the only difference being the loss in NPV going up to $43.65 from the base NPV and the difference in the discounted net revenue from the base run being $3.24 per acre at the end of year twenty.

Fertilizer application limit

A restriction on the level of fertilizer use per acre at 67 lbs (Table C.13 in the Appendix C) constitutes the next step in the analysis.[25] It results in a small change in the nitrate level in the terminal period reducing it to 13.64 mg/l from 14.76 mg/l in the base run while there is a moderate fall in the discounted net revenue from around $217.51 /acre in the base run to $210.02/acre at the end of the terminal period. No noticeable change is observed in the behavior of the saturated thickness and pumping lift over time when compared to the base year values. However the main difference with the imposition of the constraint in Castro and Lubbock is that, in Lubbock the constraint is accompanied by a large opportunity cost. These large values might be partly attributable to the fact that any departure in the base solutions as far as the use of the inputs is concerned, imposes a large penalty on the objective function that gets reflected in the additional constraint.

[25]Below this level the model is found to be infeasible. A possible reason might be that there is some optimal level of fertilizer that should be used per acre and below that application level no feasible solution exists given the bounds on the input application levels.

The two broad water conservation policies followed here are the quota on irrigation water use and the water rights buyout. Both these policies have been discussed at length for Castro County. On the other hand the policy designed to conserve the water stock through a restriction on the saturated thickness level is not considered for Lubbock since the fall in the latter is found to be merely 21% at the end of the terminal period for the base run. The decline in water table and the resultant practice of adopting dry land irrigation in parts of West Texas including Lubbock indicate that rational use of groundwater is more essential rather than merely conserving the stock.

Quota on water use and buyout of water rights

The imposition of the quota of irrigation water use (Table C.14) shows an average of 3.32 acre inches of water use and around 1.66 feet difference with the base run in the final period pumping lift. These translate to a decline in the average pumping cost of 13% in year 20 as compared to the base run. Yet the fall in cost per acre fails to dominate the huge loss in discounted net revenues of $72.59 per acre on average. In contrast, the agent stands to gain the most from the buyout policy (Table C.15 in the Appendix C) which also predictably, has the maximum influence on the change in water stock. For the buyout policy, an average irrigation water use of 2.82 acre inches / year leads to an increase in pumping lift of 9.34 feet at the end of the final year amounting to a water withdrawal cost of only $1.23 per acre on average compared to $1.64 per acre for the base run. However there is no positive impact on the pollutant stock over time which corresponds to the base values. But the discounted net revenues on average climbs up to $ 223.04 per acre from that in the base run of about $218.19 per acre, or a net gain in NPV of $73.18 per acre from the base value. Once again the price offered to users for giving up their water rights is calculated from a water demand and supply constraint included in the base model. This constraint essentially limits the net demand for water to the net stock available over time in the county for all irrigated acres.

Table C.16 describes the effect of the buyout policy when combined with a restriction on fertilizer application level. As opposed to just the water rights buyout policy, it affects the nitrate stock to some extent (it falls to 13.64 mg/l in year 20) but reduces the net revenues over the planning horizon. The effect on all other variables remains the same. However the loss of $2.12 per acre in net revenues indicates that there is a tradeoff involved in the regulator's decision to achieve a slightly better water quality level by limiting the use of fertilizer per acre. For Lubbock, as may be observed from the policies above, the pollutant stock has been going down over the years. Hence rational use of the water may take on a prioritized role if a policy of regulating the use of the inputs is to be implemented.

Table V.3 below provides a synopsis of the differences in discounted net revenues over time for the various policies and the base solution.

Table V.3: Change in discounted net revenues per acre over the twenty year planning period

years	base $/acre	nitp_0.53 $/acre	nitp_0.55 $/acre	constraint $/acre	quota $/acre	buyout $/acre
1	218.87	-1.94	-3.23	-7.48	-72.76	5.33
2	218.80	-1.94	-3.23	-7.47	-72.74	5.29
3	218.74	-1.94	-3.24	-7.48	-72.73	5.25
4	218.67	-1.94	-3.24	-7.48	-72.71	5.22
5	218.60	-1.94	-3.24	-7.48	-72.69	5.19
6	218.53	-1.94	-3.24	-7.48	-72.67	5.17
7	218.46	-1.94	-3.24	-7.48	-72.66	5.20
8	218.39	-1.94	-3.24	-7.48	-72.64	5.23
9	218.31	-1.94	-3.23	-7.48	-72.62	5.27
10	218.24	-1.94	-3.23	-7.48	-72.60	5.30
11	218.17	-1.94	-3.24	-7.48	-72.59	5.33
12	218.09	-1.94	-3.23	-7.48	-72.56	5.37
13	218.02	-1.94	-3.24	-7.48	-72.55	5.40
14	217.94	-1.94	-3.23	-7.48	-72.53	5.44
15	217.87	-1.94	-3.23	-7.49	-72.51	5.47
16	217.80	-1.94	-3.24	-7.49	-72.50	5.50
17	217.72	-1.94	-3.23	-7.48	-72.47	5.54
18	217.65	-1.94	-3.23	-7.49	-72.46	5.57
19	217.58	-1.94	-3.23	-7.49	-72.44	5.54
20	217.51	-1.94	-3.23	-7.49	-72.42	5.53

Note: *nitp_0.53* and *nitp_0.55* refer to price of fertilizer being raised by 5% and 10% respectively. *constraint* refers to the limit on fertilizer application of 67lbs/acre.*Quota* denotes the restriction of irrigation water use by $0.50 per acre inch from the average base value. *satt_50* refers to the saturated thickness being restricted to 50 feet at the end of the terminal period, while *buyout* denotes the purchase of water rights by around 2 acre inches per acre by the Groundwater Conservation District.

As seen above the water buyout policy leads to an average increase of $5.36 per acre in discounted net revenues over the base values while the agent incurs a loss of $72.59 on average due to the restriction on water use.

Table V.4and Figs.V.3and V.4below show the effect on saturated thickness and nitrate concentration over the twenty year time period for Lubbock County

Table V.4: **Change in saturated thickness over the twenty years for the base situation and the different policies**

years	base feet	nitp_0.53 feet	nitp_0.55 feet	constraint feet	quota feet	buyout feet
1	60.00	60.00	60.00	60.00	60.00	60.00
2	59.38	59.38	59.38	59.38	59.46	59.54
3	58.75	58.75	58.75	58.75	58.92	59.08
4	58.12	58.12	58.12	58.11	58.37	58.61
5	57.48	57.48	57.48	57.47	57.81	58.14
6	56.83	56.83	56.83	56.81	57.24	57.66
7	56.17	56.17	56.17	56.15	56.67	57.17
8	55.50	55.50	55.50	55.48	56.10	56.68
9	54.83	54.83	54.83	54.81	55.51	56.19
10	54.15	54.15	54.15	54.13	54.92	55.68
11	53.46	53.46	53.46	53.43	54.32	55.17
12	52.76	52.76	52.76	52.73	53.72	54.66
13	52.07	52.07	52.07	52.04	53.12	54.15
14	51.38	51.38	51.38	51.34	52.52	53.64
15	50.69	50.69	50.69	50.65	51.92	53.13
16	50.01	50.01	50.01	49.96	51.32	52.62
17	49.33	49.33	49.33	49.28	50.73	52.12
18	48.66	48.66	48.66	48.61	50.15	51.63
19	48.00	48.00	48.00	47.95	49.58	51.14
20	47.35	47.35	47.35	47.29	49.01	50.66

Note:*nitp_0.53* and *nitp_0.55* refer to price of fertilizer being raised by 5% and 10% respectively. *Constraint* refers to the limit on fertilizer application of 67lbs/acre. *Quota* denotes the restriction of irrigation water use by $0.50 per acre inch from the average base value. *satt_50* refers to the saturated thickness being restricted to 50 feet at the end of the terminal period, while *buyout* denotes the purchase of water rights by around 2 acre inches per acre by the Groundwater Conservation District.

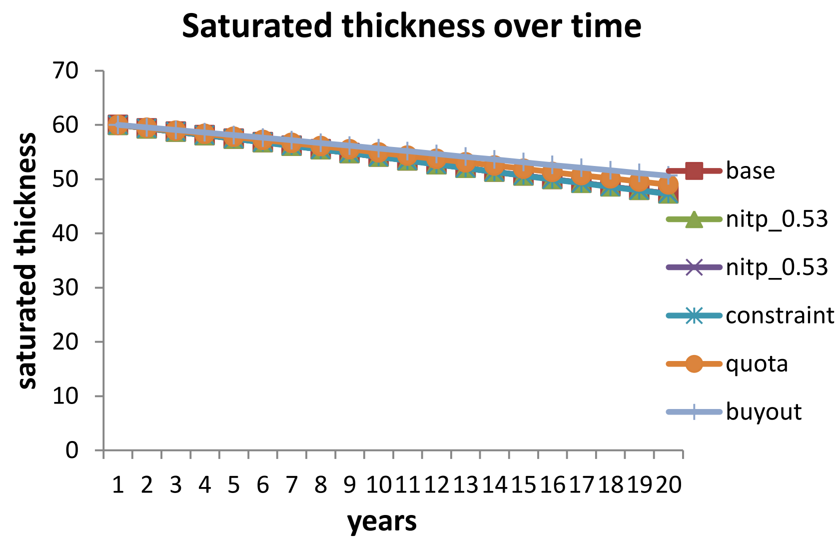

Fig.V.3: The time path of saturated thickness of the aquifer in the twenty year period for the base run and the different policies

Interestingly both the quota and the water rights buyout policies result in the least fall in saturated thickness while the policies that solely take care of the pollutant stock, specifically the constraint on the fertilizer application and the fertilizer price increases, fail to have any impact.

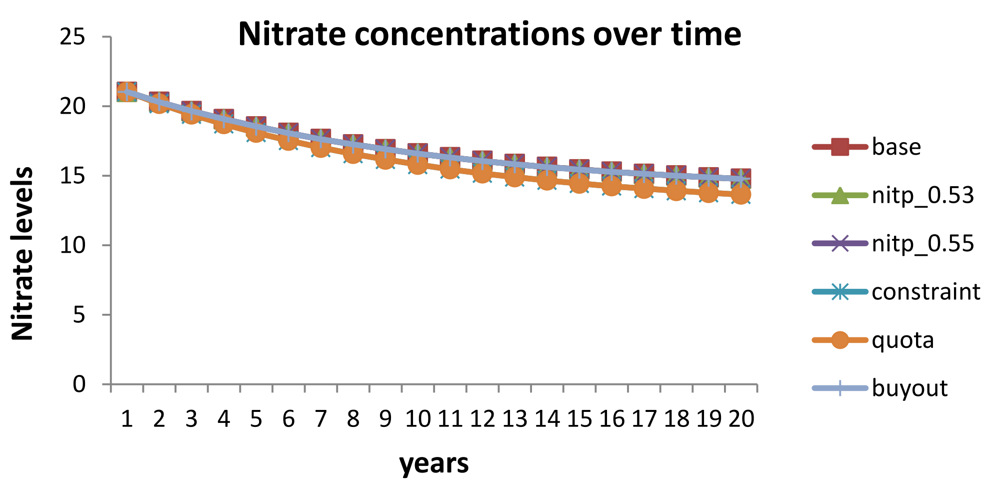

Fig. V.4: The time path of the nitrate level in the aquifer in the twenty year period for the base run and the different policies

An important difference in the behavior of the pollutant stock over time when compared to Castro County is that for Lubbock, the stock gradually falls over time the base solution and for the different simulations. Except for the quota on water use and the constraint on the fertilizer use (when the terminal period pollutant level goes down to 13.63 mg/l), there is no change in the dynamics of the stock from the base values over the entire time period.

In theory and as has been reported in different studies on the Southern High Plains, continued irrigation and low saturated thickness have consistently depleted the water level along with pushing up the nitrate levels in counties like Lubbock, Lynn and Terry. The economic cost incurred in water withdrawal falls to a large extent during the twenty years of simulation primarily when policies to curb the use of water are imposed. However, the quota of restricting water use to around 0.50 acre inches / acre less than the average base use has positive impact on the level of water but severely affects the discounted revenues on average. Yet when combined with the restriction on the use of fertilizer per acre, the quota turns out to have a positive impact on the water quality, which is reasonable given that irrigation water and fertilizer are the two main control variables in the model.

The moderate fall in saturated thickness for the base scenario as well as for the different options explored is encouraging as is the fact that there is a fall in the pollutant stock over time. As mentioned, a gradual tendency towards using less of irrigation water (and hence less of fertilizer use), adoption of more advanced water efficient techniques and recent application of surface water irrigation are possible reasons that might be forwarded. For the same reasons the water rights buyout policy repeats the success of

Castro County in terms of conservation of groundwater and putting a financial incentive on the agents. In a way this policy demonstrates the need to economize on the already scarce resource of groundwater but at the same time not compromising on the discounted revenues of the agents dependent on it. Nevertheless, it needs to be emphasized that the results shown above for Lubbock tell a somewhat different story from what was obtained for Castro County. For one, there is a difference in the effects of the policy of curtailing the use of fertilizer per acre —this had a favorable outcome for the management of groundwater for Castro while having hardly any effect for Lubbock over the twenty year period. Same may be inferred for the policy of restricting the use of water per acre for Lubbock. It results in a fall in net present value of the order of $998 per acre for Lubbock County which indicates the economic value placed on the scarce resource of groundwater in these counties. For Lubbock, these opportunity costs show up in the constraint equations as well as in the objective value for NPV calculation more so for the case where water use is restricted. The discussions on the study region about the fact that cotton is the predominant crop grown in counties like Lubbock, Lynn, Hockley and Terry on account of its smaller requirement of irrigation water and the base solutions here provide further insights into this. Overall, the water rights buyout policy attains the joint quantity-quality management for both these counties and as pointed out before has definite long term policy implications.

An interesting question arises as to where the stock of water saved by buying out water rights shows up. The stock is reflected in the net gain in saturated thickness of the aquifer over the planning horizon. In so far as this water may be used at the end of the decision making period, there is a positive stock effect involved in giving up water rights now. In counties like Lubbock where the water table is low and a growing tendency towards non irrigated production is observable, this is a policy that may be pursued over a longer time period.

All of the above policies take care of the nonpoint pollution through a point source and the regulatory agency only needs to monitor the nitrate levels in groundwater, a task carried out by the Texas Water Development Board. This constitutes a second best economic outcome shifting the burden entirely on the polluter at the point source. Since the agency needs also to monitor the stock of water in the ground along with the pollution stock, it becomes imperative to justify through empirical results, the applicability of these polices in a particular year and for particular sites after weighing the costs and benefits of each option. Also, the effectiveness of each of the above policies in preserving the stock of water and minimizing the dynamic accumulation of the pollutant stock as a result of irrigated agriculture needs to be evaluated from the point of view of the policy maker's long term objective.

CHAPTER VI

WATER DEEDS APPROACH

Water Markets

The property rights regime proposed by Smith (1977) and further elaborated on by Anderson, Burt, and Fractor (1983) proposes that rights be assigned to proportions of both the stock and flow elements of a groundwater system. The outcome of this proposal is the provision of an incentive to each property right holder that removes the effects of the rule of capture and motivates each right holder to allocate the groundwater stocks over time so that the present value of marginal returns in each time period are equalized. Garrido (2000) emphasizes the importance of surface water markets for irrigated agriculture in Spain while Zeitouni et al. (1994) takes a similar static framework for efficient allocation of water rights through trading based on the price generated by solving a linear programming model. The allocation of water rights not only takes care of the agent's conservation incentives but has implications for the prevention of pollution as shown in Weinberg et al. (1993).

The essential feature of such water trading models is the shadow price generated through the water demand and supply constraint in a joint maximization problem[26]which plays the role of the bid price during the trade. The present study builds on this concept in

[26] This is the net benefit maximization problem for all agents involved in the use of water. In a competitive world the solution for this problem leads to maximization of the sum of consumer and producer surplus.

a dynamic setting for groundwater. In other words the rights traded are for the stock of water over a period of time. Fractor (1988), Provencher (1988,1993) and Provencher and Burt (1993,1994) use a proportion of the flow or recharge as well as the stock of groundwater as shares to demonstrate the benefits of water trading or privatization of groundwater rights as compared to its use as common property. Fractor (1988) points out the differences between central control of the water stock and a private property regime and introduces a reaction function which accounts for the user cost on the neighboring agent due to present extraction of water by any agent. He analyzes private property regime in terms of the entire user cost that should be internalized by an agent. Private property rights are assumed by Provencher (1988, 1993) as stock shares with the price of the stock controlling the decision of an agent to over pump groundwater or not. His empirical results demonstrate the use of groundwater rights that influences pumping rates as deviations from observed behavior under a common property framework. Provencher and Burt (1993, 1994) on the other hand, bring in the risk element associated with stochastic surface water flows as the reason to privatize the stock of ground water in a competitive market. They compare the private property regime with a centralized regulatory regime and show that the former may yield greater welfare because of its ability to cope with the income risk. Our objective in this study is to introduce a permit trading under a common property and rule of capture regime in Texas. Agents are assumed to be risk neutral and they want to draw as much water as possible. However, a transferable property rights system is found to induce efficient allocation of water use among the agents.[27]

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[27]The above studies were done for Madera and Kern counties in California and the present study introduces the concept for West Texas.

The rule of capture or the absolute ownership doctrine characterizes Texas groundwater use. In one sense it vests absolute ownership of water underlying the land and in another it relates ownership to beneficial use of the water. In most cases the former interpretation predominates. However, the groundwater conservation districts in Texas work alongside the regional planning bodies like the Texas Water Development Board (TWDB) and the Texas Commission on Environmental Quality (TCEQ) to ensure that this absolute ownership does not translate into a situation where landowners exercise a monopoly over groundwater. The High Plains Underground Water Conservation District (HPUWCD) #1 created in 1951 serves as the planning and management body for conservation of the Ogallala water for fifteen counties of West and Central Texas.[28] The major responsibilities covered are distributing permits to drill a well and get them registered with a governing water body (e.g. TWDB), controlling the drawdown in the water table, setting spacing limits for well drilling,[29] permission to buy or sell or groundwater and more importantly, requiring any well owner to obtain permits to export water out of his domain. The last mentioned responsibility gives this Groundwater Conservation District (GCD) the power of a regulatory agency who determines a reasonable fee for distribution or sale of groundwater rights among different landowners. In addition, the GCD has the authority to impose regulatory limits on groundwater contamination levels given its connection with the regional planning body, the TWDB. The GCD can distribute the initial level of permits for drilling well(s) and along with

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[28]The High Plains Underground Water Conservation District No. 1 (HPUWCD) service area (shown in blue) consists of Bailey, Cochran, Hale, Lubbock, Lynn, and Parmer Counties, as well as portions of Armstrong, Castro, Crosby, Deaf Smith, Floyd, Hockley, Lamb, Potter, and Randall Counties. An area of 10,728 square miles or 6,865,920 acres is served by the Water District.

[29] According to Texas Water Code 36.116, by separating the wells GCD may prevent the formation of the cone of depression.

TWDB determine the maximum stock of water available for transactions by individual farmers who can buy and sell entitlements or water rights. Also as a regulatory agency, the GCD can impose a reasonable fee for transporting water out of the conservation district and review and limit the amount of water being transferred under a permit.

In the map below the eleven counties that come under the HPUWCD#1 are shown.

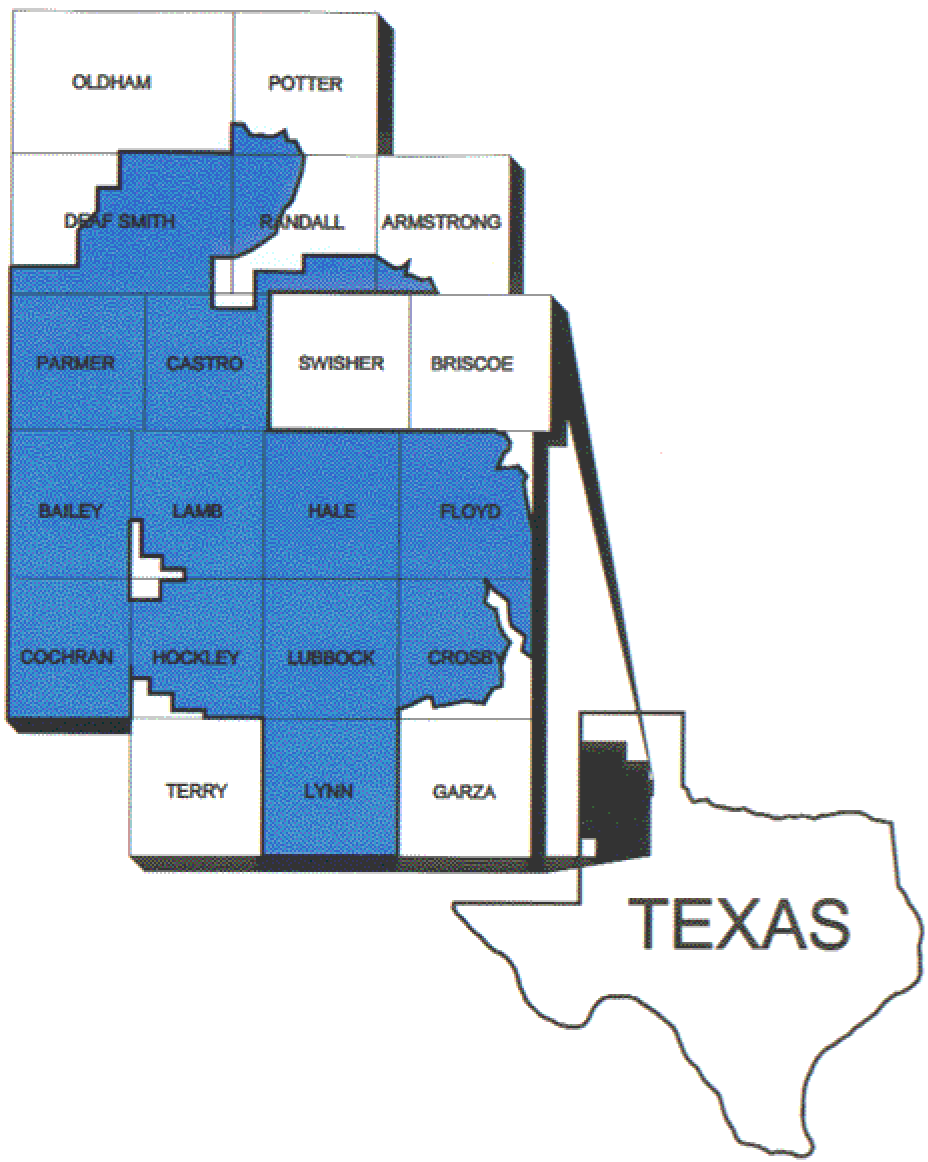

Fig. VI. 1: The High Plains Underground Water Conservation District#1

The chapter proceeds in the following manner. The section below describes a benchmark model where a myopic user or a producer with limited foresight uses as much resources as possible in the present time period. Next the main characteristics of an agent based trading model are laid out. The empirical version of the model and the results are discussed in the next section. The chapter ends with a brief conclusion about the merits of such permit trading in groundwater.

Myopic model

The myopic model may be viewed as one with limited foresight where an agent draws water from the aquifer without consideration about the effect of her withdrawal on the remaining stock of water and thereafter on the pumping cost of extraction. This behavior leads to a faster depletion of the aquifer if all myopic agents ignore the inter temporal stock effect, a phenomenon which closely resembles the case of the rule of capture in Texas.

In the following optimization model it is assumed that a single agent uses water and nitrogen as inputs for his production and is free to use as much of these inputs. She owns 530 acres of land divided among four crops viz. corn, cotton, sorghum and wheat. She faces a constant marginal cost of pumping (C_0) and the total cost of pumping is given by $C_0(SL - S_t)$ where SL is the height of the surface level (Burness and Brill, 2001). A higher pumping lift thus influences the total cost of extraction—however, the myopic agent does not take this into account as far as its impact on the net inter temporal extraction from the aquifer is concerned. Her own cost of pumping gets affected but she ignores the pumping cost repercussion inflicted on other agents due to her uninhibited withdrawal of water. Her optimization model takes the following form:

$$Max \sum_{t=0}^{T-1} \beta^t \, [\{B(x_t, m_t) - C_t * x_t - d_t\}] \tag{6.1}$$

subject to

$$S_{t+1} = S_t + \{R— (1 - \alpha) * x_t\}/AS \tag{6.2}$$

$$C_t = C_0(SL - S_t). \tag{6.3}$$

$$M_{(t+1)} = \eta l_t + \ (1 - \delta)M_t \tag{6.4}$$

Where C_t refers to the total cost of pumping water, L_t refers to the number of irrigated acres and non-pumping costs $d_t$affect net revenues in (6.1). Everything else is as defined before. S_t refers to the saturated thickness of the aquifer, R is the almost constant average recharge rate, α denotes the proportion of return flow from irrigation, AS represents the product of the storativity times the area of the aquifer and finally, $M_t$refers to the nitrate level in the aquifer at any time period t.

Table VI.1 presents the dynamic behavior of the myopic agent over the twenty year time period. The results show similarities to those obtained in the unconstrained joint maximization solution for Castro County. A somewhat uniform use of irrigation water and fertilizer use per acre is observed with around 9.7 ac-inches/acre of water use and 157 lbs./acre of fertilizer use over the time horizon. It may be noted that she maintains a steady demand for water and fertilizer, and actually contributes to a consistent rate of nitrogen percolate over time. If all such agents were homogenous in their use of the inputs, a direct consequence may be noticeable in the quality of the water —the nitrate level goes up by 8.61mg/l on average from the initial value of 6.37mg/l. However, there is very little difference on the level of water stock (saturated thickness or pumping lift) over time and as will be shown later the values are similar to those obtained in the permit trading model. One possible reason might be that the model is representative of a single agent. The effect on the stock of water in the aquifer gets magnified when a large number of myopic users are considered. The average change in pumping lift and saturated thickness for the aquifer amounts to 0.07 feet and 0.94 feet respectively which may be extrapolated to find the net effect on both from all such users. On the other hand the change in pollutant stock reflects the addition of the percolate that contributes to the groundwater pollution and is a measure of the overall nitrate stock in the aquifer when every myopic agent on average acts in a similar manner.

Table VI.1: Results from myopic model

years	irr	fert	percolation	nitconc	satthickness	plift	pcost	discounted NR
	ac-in/acre	lbs/acre	lbs/acre	mg/liter	feet	feet	$/ac-in	$/acre
1	9.68	156.87	81.61	6.37	79.00	233.00	5.26	95414.28
2	9.68	156.87	81.61	7.37	79.00	233.01	5.26	95414.28
3	9.68	156.87	81.61	8.26	78.99	233.01	5.26	95414.28
4	9.68	156.87	81.61	9.07	78.99	233.02	5.26	95414.28
5	9.68	156.87	81.61	9.79	78.98	233.02	5.26	95414.28
6	9.68	156.87	81.61	10.45	78.98	233.03	5.26	95414.27
7	9.68	156.87	81.61	11.03	78.97	233.03	5.26	95414.27
8	9.68	156.87	81.61	11.56	78.97	233.03	5.26	95414.27
9	9.68	156.87	81.61	12.04	78.96	233.04	5.26	95414.27
10	9.68	156.87	81.61	12.47	78.96	233.04	5.26	95414.27
11	9.68	156.87	81.61	12.85	78.95	233.05	5.26	95414.27
12	9.68	156.87	81.61	13.20	78.95	233.05	5.26	95414.26
13	9.68	156.87	81.61	13.51	78.94	233.06	5.26	95414.26
14	9.68	156.87	81.61	13.79	78.94	233.06	5.26	95414.26
15	9.68	156.87	81.61	14.05	78.93	233.07	5.26	95414.26
16	9.68	156.87	81.61	14.27	78.93	233.07	5.26	95414.26
17	9.68	156.87	81.61	14.48	78.92	233.08	5.26	95414.26
18	9.68	156.87	81.61	14.66	78.92	233.08	5.26	95414.25
19	9.68	156.87	81.61	14.83	78.91	233.09	5.26	95414.25
20	9.68	156.87	81.61	14.98	78.91	233.09	5.26	95414.25

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *perc* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satt* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *netrev1*and*netrev2*represent the discounted value of net revenues over the years from this activity.

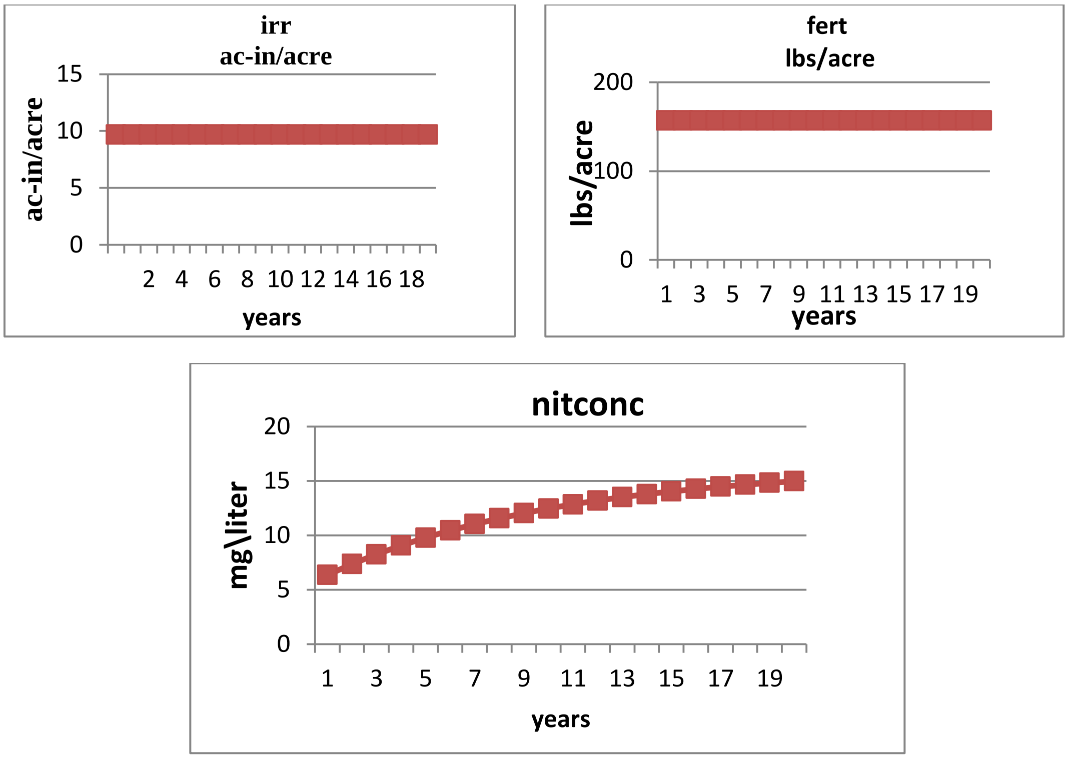

Fig.VI.2: **The time paths of the two primary inputs and the pollutant stock for the myopic model**

It may be observed from the dynamic paths above that a myopic user has very little incentive to reduce the consumption of the two inputs. As a result, the stock of pollutant in the water will tend to increase over time if all such myopic users are free to operate under the rule of capture.

Agent level modeling

Before going to an individual agent's profit maximization problem in the presence of permit trading the following primary characteristics of a permit market are briefly laid out. (i) The permit market is competitive, transparent and well defined in nature. (ii)The permit price will evolve dynamically but is the same and exogenous for water traders in each period. (iii)If the market is competitive, a well defined trading market would allocate permits efficiently as well as cost effectively. (iv) Considers full information and at equilibrium the shadow price obtained from the permit market clearing equation will correspond to the permit price at each period. (v) Conventionally, the basis for a tradable permit to work in the case of water extraction would be the difference in the marginal cost of pumping in the myopic/competitive case—the one with a higher cost of pumping would like to purchase stock while one the lower cost of pumping would like to sell off. (vi) Transaction costs are an important feature of permit trading and as will be discussed later influence the economic feasibility and magnitude of trade (vii) Finally, a tradable permit regime can encourage technical innovation so as to lower the cost of extraction and also conserve the rate of use of water.

In this trading model it is assumed at the outset that a central agency like the Groundwater Conservation District (GCD) issues permits based on the ownership of land and the rights to the water below it. (A lot depends upon the historic use of the water and the GCD has the ability to limit the maximum amount of water that may be drawn from a single well). The permits are allocated and traded in terms of acre inches of water stock each period.[30] The sale or purchase of the permits is dictated by the extent to which the value of the marginal product of water compares to the permit price from the point of view of an agent. Hence an agent with a relatively higher demand for water may make a long term decision to purchase permits. Though in the empirical model, we abstain from the possibility that the net purchaser of permits can turn into a net seller at least within the time period under consideration, it may not be ruled out completely. It should be

[30] Usually water rights are traded in terms of acre feet, but since irrigation water used is expressed in acre inches the latter is taken as the unit of measure just for the sake of simplicity.

noted that the initial amount of “permits” allocated will affect the eventual stock being held by each agent.

A two agent model of a permit trade is hypothesized for Castro County in West Texas. The individual farms correspond to an average size of 600 and 530 acres respectively (Texas fact sheet, ERS[31]) and the average well yield exceeds 25,000 gallons a day which implies that according to present GCD rules both are entitled to receive some initial set of transferable property rights for a certain stock of aquifer water in storage which is some fraction of the total stock of water in aquifer (determined by the GCD on the basis of the number of irrigated acres across the county and the projected water stock overlaying the county). Specifically the allocation of water stock to each agent is determined in the following manner. The TWDB County Report for Castro County has the projected storage for the Ogallala for each level of saturated thickness starting from 2000 and ending in 2020. The stock corresponding to the initial saturated thickness of the aquifer for Castro in 2010 is taken to be the net storage of water for the aquifer in the county. Each agent irrigates a particular proportion of the total irrigated acreage of the County and that proportion is considered while making decisions about the initial stock of water that each agent is entitled to. The idea conforms to the production limit set by any GCD “based on property area controlled by a well operator”[32] and corresponds to the original proposal of water deeds by Vernon Smith. Each agent may have a number of wells or a single well that can be used to access aquifer water for irrigation. The pumping efficiency of the wells is taken as constant and the irrigation technology used is the Center Pivot with 90 % efficiency and this is also fixed. It is assumed that the first agent

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[31] Economic Research Service
[32] Production limit= acre feet of water*acreage owned.

owns a farm covering 530 acres while the second owns a farm of size 600 acres, with each individual growing four crops—corn, cotton, wheat and sorghum. The irrigated acres for each crop for each agent are calculated on the basis of the average proportion of irrigated acres from 1987-2009 data for crops as obtained from NASS. The production functions for the crops and the nitrogen percolation functions are estimated from simulated data generated by CRopman (Gerrick et al. 2003).[33] The water withdrawals of both agents have an impact on the saturated thickness and the pumping lift of the aquifer and thus the pumping cost depends upon the water use of both agents. The second agent with a higher initial stock and lower demand for water is assumed to sell permits to the first agent and any transaction with a third party for purchase or sale of permits is not considered. Thus a twenty year market trading model is simulated with one agent as a net purchaser of permits and the other a net seller of permits. The stock of water available to the second agent may be conserved if she purchases water from a third party but to keep the model simplistic any sequential trading through exchange of permits with multiple agents and hence updating the equilibrium stock for all is assumed away. Initially the GCD assigns a stock of 2035 acre inches of water to the first agent and 2604 acre inches of water to the first agent, the difference explained by the proportion of acres irrigated by each. It is assumed that around 35-40% of the permits held may be sold each period to the first agent, thus putting a cap or limit on the maximum number of permit transactions in each period.[34] This limit ensures that the agent does not end up selling all her stock in any period which is an extreme case of the seller either wishing to leave the market or resorting to dry land farming.

[33] The estimated relationships for Castro County are shown in the appendix.
[34] Refer to Rubin (1997) for a theoretical exposition. In the empirical model this cap was decided on the basis of the impact of permit transfer on the output, costs and net revenue of the seller.

Computation of permit price

The permit price is obtained from the joint maximization solution where the net demand for water is equated to the total stock available every period. Thus in the agent level modeling it is exogenous every period. This price may also emerge from the model solution each period as shadow prices from a market clearing equation. However, this endogenous solution showed a wide variation in the prices over time, so the agent model is solved with prices as given. It is also implicitly assumed that the permit price from the joint maximization problem incorporates the water transaction costs.

Trading model

Prior to introducing the empirical model, a distinction may be made between simultaneous and sequential trading models as popularly known in the environmental pollution literature. A simultaneous permit trade minimizes the cost of pollution abatement subject to reducing the local emissions to some pre- specified levels. The trade goes on among all parties involved based on their marginal cost of abatement. In a sequential trade, bargaining is carried out between two parties based on the difference in their marginal costs of abatement and the bilateral trade ends when the air quality criterion is satisfied at a feasible cost which is lower than the usual control cost. The next round of trade does not involve the above parties. Atkinson and Teitenberg (1991) came to the conclusion through their empirical study that a sequential bilateral trade is suboptimal and results in lower cost savings than simultaneous trading. Hung and Shaw (2005) extended the sequential trading procedure laid down by Atkinson and Teitenberg to a transferable discharge permit system for a zonal pollution problem. They noted that with perfect information about the transfer coefficients in each zone and the authority's control over the cap on zonal effluents, the sequential trade is optimal and cost effective. The model shown here applies the bilateral trading approach to the stock of water that is traded and is a much simplified version of the sequential trading approach as illustrated by the above authors. Through permit transactions every year, a cost effective feasible trade is consummated by the purchaser and seller of permits. The distinguishing feature of this model is that the "sequential" bargaining procedure results in a higher net revenue for both agents compared to what they earn in a purely myopic situation. However the cost effectiveness remains a major determinant of the time span for the trading relationship.[35]

The intuition behind the following empirical model comes from the concepts in Hung and Shaw (2005). However, the equations of motion follow from the model suggested by Smith (1977) and later used in a theoretical paper by Provencher (1988). Assuming as above that the initial stock of water is given for each agent and denoting the stock held by agent 1 as V_{1t} and that by agent 2 as V_{2t} and permits by G_t every period, the state equations for motion for groundwater trading may be described by:

$$V_{1(t+1)} = V_{1t} + G_t - x_{1t}$$

Where x_{1t} refers to the total amount of irrigated water extracted by agent 1.

Similarly for agent 2,

$$V_{2(t+1)} = V_{2t} - G_t - x_{2t}$$

Where x_{1t} refers to the total amount of irrigated water extracted by agent 1 (let L_{1t} be the number of acres irrigated by her) and x_{2t} defined similarly for agent 2.

[35] The empirical model solves the entire problem simultaneously. The most that can be achieved in terms of a sequential bargaining is the recursive solution technique which encountered model infeasibility in the second period itself.

At every period it is assumed that agent 1 is a net seller of permits and agent 2 is a net purchaser of permits. The amount of permits at agent 2's disposal can be calculated as:

$$G_t = V_{2t} - x_{2t}$$

Let g_t denote the permit price at any period and as mentioned above the value of $g_t$is given from the joint maximization problem. The scalar γ refers to the limit on the amount of permits sold at a given time period. Also, it is assumed that x_t is the net water extraction by the two agents and m_{1t} and m_{2t} are the amounts of fertilizer applied respectively by agent 1 and agent 2.

Then the empirical model can be mathematically summarized as:

$$Max \sum_{t=0}^{T-1} \beta^t \, [\{B(x_{1t}, m_{1t}) - C(V_{1t})x_{1t} -* \gamma g_t G_t\}] + \left\{B\left(x_{2t}, m_{2t}\right) - C(V_{2t})x_{2t}\right\}] \tag{6.4}$$

subject to

$$S_{t+1} = S_t + \{R - (1 - \alpha) * x_t\}/AS \tag{6.5}$$

$$V_{1(t+1)} = V_{1t} + \gamma G_t - x_{1t} \tag{6.6}$$

$$V_{2(t+1)} = V_{2t} - x_{2t} - \gamma G_t \tag{6.7}$$

$$G_t = V_{2t} - x_{2t} \tag{6.8}$$

$$x_{1t} \leq V_{1t} + \gamma G_t \tag{6.9}$$

$$M_{(t+1)} = \eta l_t + \ (1 - \delta)M_t \tag{6.10}$$

The first term in the objective function denotes the net benefits accruing to the purchaser of permits, the second term refers to the net benefit function of the seller. The second agent or the seller may hold the property rights to the stock of water and hence has an influence on the amount of permits sold. Thus (6.4) is not a joint benefit maximization or a social planner's problem but mimics a firm level market trading activity where price equals the marginal cost for each agent. Alternatively, it is not the social surplus that is captured by the solution but the individual net revenues earned, based on which the trade is continued every period. To preserve clarity the permit revenue is not added to the second individual's net benefit function but in the empirical version the permit revenue appears in the net benefit equation for each individual agent. Equation (6.5) describes the state equation for the saturated thickness measured in feet while equation (6.9) imposes a constraint on the total stock of water available for agent1. Equation (6.10) refers to the nitrate stock relationship over time as described in Chapter IV.

Table VI.2 shows the main results from the permit market trading for the twenty year time period. The average use of irrigation water is 8.56 per acre while the average use of fertilizer is 118.67 lbs per acre, the latter being much lower than what was obtained in the base case. What is notable is the gradual decline in the use of water per acre which might be a consequence of the stock of water getting diminished for each individual agent particularly in the later years. The transaction of permits allows both agents to reallocate water in such a way that they end up with finite stock at the end of the twenty years and also maintain levels of output for the crops comparable to the base run. The permit market solution actually leads to a favorable impact upon water quantity and quality. At a more disaggregated level, this version of trade takes into account each agent's net benefit every period so that each can revise her demand for water and fertilizer independently and then reallocate the inputs to the highest valued use.

Table VI.2: Effects of permit market trading

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	satthickness feet	plift feet	pcost $/ac-in	nitconc mg/l	net rev1 $	net rev2 $
1	9.67	123.02	28.10	79.00	233	6.45	6.37	120890.12	127097.28
2	10.92	123.02	17.01	78.99	233.01	7.28	6.30	115304.15	131677.33
3	10.07	123.02	28.86	78.98	233.02	6.72	6.01	115739.84	130365.22
4	9.86	123.02	31.95	78.97	233.03	6.58	5.98	116150.16	129458.09
5	9.86	123.02	31.95	78.96	233.04	6.58	6.02	116558.87	129049.37
6	9.86	123.02	31.95	78.95	233.05	6.58	6.06	116967.58	128640.66
7	9.86	123.02	31.95	78.94	233.06	6.57	6.09	117375.94	128182.96
8	9.17	121.9	31.43	78.93	233.07	6.12	6.11	117723.37	117576.24
9	7.99	114.76	31.43	78.93	233.07	5.33	6.13	117959.59	96944.91
10	7.97	114.76	31.87	78.92	233.08	5.31	6.15	118185.08	96280.89
11	7.52	114.76	42.61	78.91	233.09	5.02	6.39	118370.35	84629.92
12	7.46	114.95	44.64	78.91	233.1	4.97	6.65	118311.91	82134.44
13	7.49	115.26	44.64	78.90	233.1	5.00	6.87	118085.17	81960.34
14	7.53	115.57	44.64	78.89	233.11	5.02	7.08	117854.68	81751.45
15	7.57	115.89	44.64	78.89	233.12	5.05	7.26	117656.08	81467.23
16	7.61	116.22	44.64	78.88	233.12	5.08	7.43	117385.11	81206.17
17	7.66	116.55	44.64	78.87	233.13	5.11	7.58	117000.27	81003.03
18	7.7	116.89	44.64	78.87	233.14	5.14	7.72	116261.84	81089.59
19	7.75	117.23	44.64	78.86	233.14	5.17	7.84	115583.34	81042.86
20	7.8	117.59	44.64	78.85	233.15	5.21	7.95	115075.11	80741.16

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *perc* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satt* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *netrev1*and*netrev2*represent the discounted value of net revenues over the years from this activity.
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Table VI.3: Stock held and permits transacted during the trading period

years	stockwater A1 ac-inch	stockwater A2 ac-inch	pcost A1 $/ac-in	pcost A2 $/ac-in	permits ac-inch	permit price $/ac-in
1	4908	61140.00	6.63	6.24	59683.01	0.30
2	8160	59683.01	6.63	8.02	53722.38	0.30
3	9743.67	53722.38	5.56	8.02	48714.29	0.30
4	17984.91	48714.29	5.30	8.02	43945.99	0.30
5	24795.66	43945.99	5.30	8.02	39177.69	0.30
6	30175.92	39177.69	5.30	8.02	34409.39	0.30
7	34125.69	34409.39	5.29	8.02	29645.52	0.30
8	36646.29	29645.52	4.36	8.02	25652.87	0.30
9	37969.11	25652.87	2.95	8.02	23002.58	0.30
10	38496.83	23002.58	2.89	8.02	20373.53	0.30
11	38235.84	20373.53	2.32	8.02	18252.00	0.30
12	37338.39	18252.00	2.26	8.06	16224.00	0.30
13	35807.68	16224.00	2.26	8.12	14196.00	0.30
14	33627.47	14196.00	2.26	8.17	12168.00	0.29
15	30795.95	12168.00	2.26	8.23	10140.00	0.25
16	27311.13	10140.00	2.26	8.29	8112.00	0.20
17	23170.80	8112.00	2.26	8.34	6084.00	0.15
18	18372.46	6084.00	2.26	8.34	4056.00	0.30
19	12913.37	4056.00	2.26	8.34	2028.00	0.52
20	6790.39	2028.00	2.26	8.34	.	0.52

Note: *StockwaterA1* refers to the water stock in acre inches held by agent A1 in the time period, *StockwaterA2* refers to the same for agent A2, *pcostA1* and *pcostA2* refer to the pumping cost per acre inch incurred by A1 and A2 respectively and*permits* are the actual excess stock at the disposal of agent A2.

The second and third columns in Table VI.3 show the dynamic stock levels for each period for the two agents where agent 2 sells off around one third of her excess stock as permits to agent 1. A close inspection of the last column reveals that the amount of permits transacted steadily fall off after the eleventh time period when the stock of water held by each agent gradually goes down. (This may be the point where trading roles might be reversed if that option was present). Under very low recharge rates as is the case for the Ogallala and the continuing demand for irrigation water this is an indication for the agents to either reduce the use of water or shift to alternative options like dry land farming. In a sense this is equivalent to the buyout policy where any agent makes a tradeoff between her current water needs and net revenues through conservation incentives given by the regulator. Turning to the discounted net revenues over time for agent 1 it falls by a mere 5% in the entire time period as a result of the transactions. This shows that resource reallocation as a result of the trade has smaller impact upon the discounted revenues of the net purchaser of permits who initially demands more water—in economic terms it is a reallocation to the highest valued user. Another important point is that agent 1 incurs lower pumping costs (refer to the fourth column in Table VI.3) calculated on the basis of the amount of irrigation water extracted per acre by each agent (on average her cost is $3.64 / acre inch). It seems to attain a steady state ($ 2.26 per acre inch) in the last eight years, something that can be attributed to the lower level of water being drawn by this agent as her stock of groundwater falls off compared to the initial levels. (The pumping cost in the myopic model is around $4.22 /ac-inch compared to the net pumping cost of $5.71/ac-inch incurred in the trading model. In the latter case, the use of water picks up gradually and there may potentially be an opportunity to reduce the consumption of water in the later years of the planning horizon). It may be recalled that the model takes the differences in the demand for water and the initial stock belonging to each agent as the basis for the exchange of permits and in addition there exist one willing seller and one willing purchaser. Trade with other willing partners is assumed away and thus the outcomes observed here are limited in their ability to illustrate any detailed multiple agent trading equilibrium where agent heterogeneity may be brought in through differences in crops grown, variation of production functions or introduction of different production technologies.

In order to check the robustness of the above results to any changes in the initial stock of water the permit model was run with slightly different levels of initial stock distributed to each agent. Apart from small differences in the irrigation water use and crop yields, no significant change was observed in the main result.

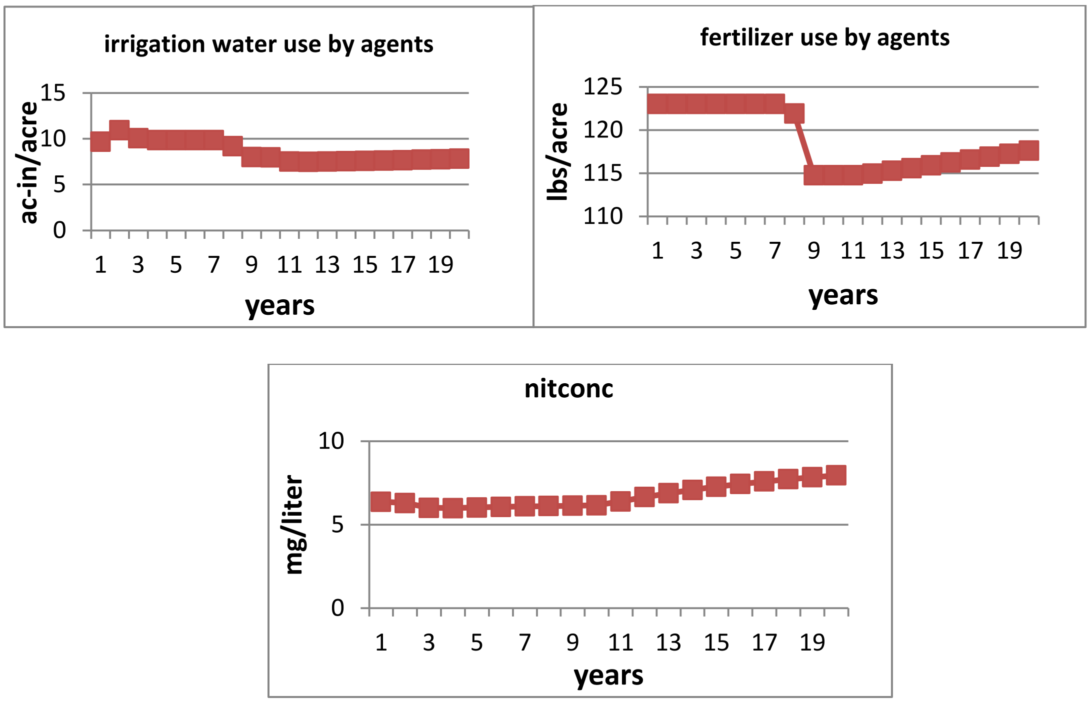

Fig.VI.3: **The time paths of the two primary inputs and the pollutant stock for the trading model**

As seen from the figures above the use of the two inputs, irrigation water and fertilizer shows a tendency to decline over time and that is reflected in the behavior of the average nitrate stock over the years of the simulation. The pollutant level remains much below the 10 MCL standards. This may be contrasted with the almost steady use of the inputs in the myopic model which is responsible for the pollutant stock showing an increasing trajectory at every time period (Fig. VI. 2).

Finally we may make a comparison of the discounted net revenues over time for the two models. Trading of stock of permits fetches higher revenues over time for both agents compared to the myopic user. In fact, as noted above (refer to Table VI.1) the revenues of the first agent goes up until year 12, while that of the myopic agent remain stable at around $95414 every year.

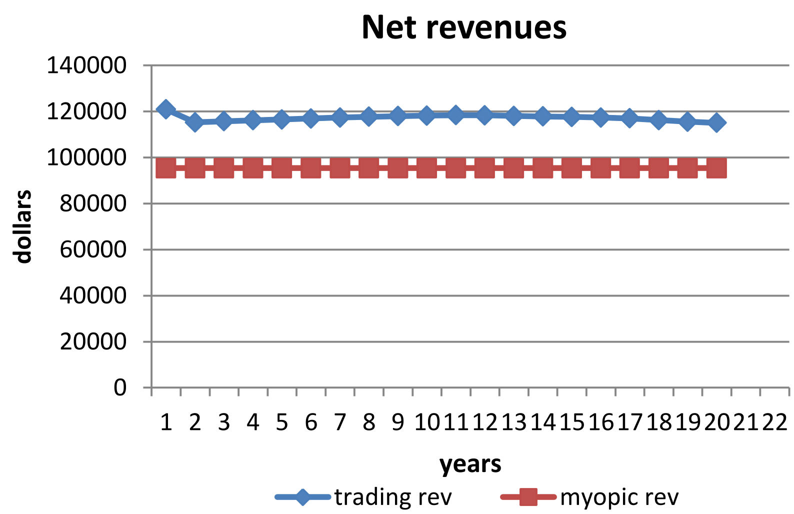

Fig.VI.4: **The time path of discounted net revenues over time for the myopic model and the trading model**

Few observations may be made about the trading model outlined here. To some extent it is similar to a Coasian bargaining solution with transfer of permits from the second agent who may be thought of as holding the initial property rights in a bilateral setting. The objective function is defined from the perspective of the first agent[36] but the constraint set restricts the stock of water traded every period, even though the former wants to maximize her net revenue. In the earlier years what is noticeable is that higher use of water by the first agent due to higher stock level-the purchaser of permits has higher demand for water. Secondly even if agent 2 incurs higher pumping costs, her net revenue through trading is higher than that in a completely myopic situation. If her value

[36] In the empirical model the net revenues or benefit functions are defined separately for each agent.

of marginal product is greater than the cost incurred for acquiring permits at any period, she has an incentive to raise her revenue through trade and trading would continue until her net profits are higher than the myopic situation. Third, the long run movement of the two main inputs in the trading model shows a declining tendency over time as shown in the diagrams with the quality of water positively affected. Fourth, the option of shifting to dry land farming during the entire time period has not been considered and may have some impact upon the main results by changing the dynamic behavior of the stock of water held. Fifth, the permit price picks up with changes in the stock of water available and a cost effective solution for the optimal number of permits traded may fall somewhere between the tenth and eleventh year. Finally, concerns about the transaction costs remain. It has been assumed here that the permit price incorporates the water transaction costs for this simple two agent trading model, an assumption that may have limited applications. Since a centralized auction mechanism to clear bids and determine prices on the lines of a “smart” market (Murphy et.al 2000) has not been followed here, the rules for trade may be laid down in a cost effective manner by the GCD which is the regulatory agency. It has to be conceded that the efficiency gains from trade over these transaction costs may not emerge until after the final trading period is over.

Strategic externality

Originally propounded by Negri (1989) and mentioned in papers by Provencher and Burt(1993), the question of strategic externality has undermined the analytical framework built for single cell aquifer models. According to Negri, groundwater being a common property resource, agents have a tendency to behave strategically in pumping water in the sense that they want to draw as much water as possible such that their neighbors do not get to do the same. This entails knowledge of the best response functions of their neighbors or other agents. However, there are two main reasons where such behavior may be written off in favor of the trading model above. First, as Brozovic et al. (2004) pointed out, strategic behavior for users is similar to a myopic behavior in a broader sense. This outcome happens because with several users of the same resource it is almost impossible for a single agent to determine the reaction function of the other agent(s) even within a single time period. Second, it may be recalled that the GCDs in Texas have laid down well spacing regulations to avert the formation of cones of depression. In such a scenario, thinking along the lines that extraction of higher levels of water now will benefit individual extraction later is equivalent to depleting one's own resource.

<u>Discussions</u>

The practice of selling or leasing out water rights is not new for states like California, Colorado, New Mexico and Texas particularly for surface water. Inter-basin or intra-basin sale of water at predetermined market prices (value of marginal product equals price rule usually followed here) has been in place for almost thirty to forty years — a clear emphasis for all these transfers is on the economic tradeoff in agricultural and municipal and industrial water use and on the price charged for the incremental/marginal acre feet of water sold. Markets designed for trading of water rights if well defined can lead to water conservation based on reallocation of water to its highest use. As Easter and Hearne (1994) have pointed out, one deficiency of such water trading in the case of surface water is often the ignorance of third party external effects. The case of groundwater trading has usually involved private water transfer between landowners and municipal users. In Texas there has been groundwater leasing or "water ranching" going on for the last 50 years. Many cities, corporations and individual well owners would buy water from rural landowners for exporting, setting up pipelines or for present use of water (Lesikar et.al, 2002). In economic terms, such an arrangement would be the transfer of water to its higher valued use.

The High Plains aquifer contributes to water needs primarily for agricultural use in the Castro county of Texas considered in this study. Given that groundwater markets may be looked upon as "thin" markets with very few traders involved in most cases, a sequential bargaining (trading) rule through exchange of permits leading to an optimal allocation of water is a cost effective solution. The nature of trading allows benefits to be shared between two involved parties with minimal third party intervention. The multilateral trading procedure is similar except for the fact that bargaining of water rights (permits) leads to an optimal allocation of resources within a common pool where price for the sale of water is determined according to the bids put forward by interested parties.(refer to Raffensperger et. al. (2009) for a detailed explanation). The present regulations for groundwater transfer or sale of permits in Texas may only allow these markets to work under very restrictive conditions. From a more practical standpoint, a sequential trading framework having an exogenous market price for water every period as described here fits well with the transfer of groundwater rights or sale experienced as of now in Texas. One drawback however, in this model is the absence of trading relationship with an external agent; the dynamics of the groundwater stock depends upon the mutual purchase and sale every period. Inclusion of another party to the trade, for instance, the municipal agency responsible for urban water supply may change the direction of trade depending upon the economic benefits of selling permits. Nevertheless, the outcomes in terms of water quantity and quality and the water conservation incentives inherent in the model described above is a step towards encouragement of more empirical studies on the working of groundwater markets in this region and may also be replicated for policy recommendations for other regions of Texas as well as through the country.

This chapter looks at the management of groundwater for a representative county in West Texas from a purely empirical standpoint. The rule of capture has been in force for a long time and is not likely to be overturned in the near future unless agents are provided incentives for leasing water rights. The GCDs in Texas encourage the sale groundwater rights at the cost of a reasonable fee and ensure that the transaction costs and third party externalities are accounted for by putting limits on the amount of water that may be transferred at a definite period of time. Thus the approach followed here takes Smith's transferable water deeds proposition to a possible trading scenario for Castro County in West Texas. Each agent is provided a property rights based incentive to reallocate the stock of water held at any period such that the water goes to the highest valued user. Though twenty periods of trading with a net purchaser and a net seller is considered in this simple model, the possibility of switching roles before this time period is not ruled out, given the marginal incentives to trade and the time path of the net revenues. From the model solution, we find that the first agent who has a demand for water is able to increase her discounted net revenue until year 12, which eventually falls off because of inherent constraints in the stock which affects the pumping cost over time. However, a desirable property of the trading model is that if conservation incentives are instilled through the net revenue and water use benefits then the myopic tendency of drawing as much water as quickly as possible (strategic externality as coined by Negri (1989)) may be reversed.

The myopic model serves as a benchmark case for comparison. The results from the myopic agent model constitute a motivation for a long run decision on permit trades for groundwater in the study region. The missing link of course, remains the determination of the actual demand for water from agents participating in the trade. The addition of the stock of water variable that changes dynamically affects the way the shadow price of water is determined for groundwater a problem that is not faced in its derivation for surface water trading. The issue here is how to best handle the remaining stock of groundwater after accounting for the individual agent use, since this stock also affects the demand for water. In addition, adoption of a different irrigation technique for reducing the cost of drawing water and the incorporation of actual transaction costs may also affect the incentives and duration of trade.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The High Plains region in West Texas overlaying the Ogallala has been the focus of water conservation policies for the last two decades because of rapid depletion of groundwater in this region. Academic researchers as well as policy planners in Texas have come up with various solutions to prevent excessive use of water for agricultural production given that the latter constitutes 95% of groundwater use in the counties of the High Plains. Quite recently, attention has been drawn on nitrate pollution of the Ogallala aquifer particularly through studies done by Hudak (2000) and Scientific Investigation reports by Gurdak and Qi (2006) and Reedy et al. (2007). The existing body of economic research dealing with groundwater extraction seems to focus only on that problem itself and does not view the exploitation of the aquifer and the corresponding pollution problem as a joint resource issue. Around 2 million people depend upon the Ogallala for drinking water purposes. Hence the importance of looking at the two problems conjunctively is related to the issue of the stock of water being unusable from the point of view of economic and consumptive needs before it even reaches the physical exhaustion level. This research attempts to fill in this gap, with the main objective being to assess the economic tradeoffs involved in groundwater quantity and quality management by capturing the dynamic behavior of the stock of groundwater as well as the stock of nitrate pollutant over a twenty year time period. Two case studies are presented for Castro and Lubbock counties in West Texas.

The study uses simulated data for the estimation of production functions and nitrogen leaching functions and those estimates are used in a dynamic optimization framework to find out the level of water and nitrogen fertilizer applied per acre that maximizes net present value over a twenty year planning horizon. The model is first solved for a base run to obtain the optimal values of irrigation, nitrogen fertilizer, nitrogen percolation below the root zone, pumping lift and saturated thickness of the aquifer, nitrate concentration in the groundwater, pumping cost of water and the net present value of production. The base solution shows that in the absence of any restriction on the amount of fertilizer use per acre for crop production, the nitrate levels go up steadily and there is a consistent fall in the saturated thickness of the aquifer. This implies that the problems of water quantity and quality are exacerbated when looked at from a joint management perspective as opposed to when the emphasis is on either.

<u>Castro</u>

Two sets of policies are developed to control the impact of excess fertilizer use on the groundwater and to evaluate the effect on the net present value of production. First, the price of nitrogen fertilizer is raised successively by 5% and 10%. With a 5% increase in the price of fertilizer, the discounted net revenue per acre falls by $4.57 from the base value in year 20 and the pollution stock accumulated falls short of the base level by 0.79mg/l. With a 10% increase in the price of fertilizer, the loss of NPV turns out to be $102.32 while the nitrate level falls by 1.27 mg/l compared to the base run. As an alternative to these exogenous changes in price of the input, the fertilizer use itself is restricted to 144 lbs./acre. This is accompanied by a mere $2.67 loss in discounted revenue per acre from the base solution and the nitrate stock goes up to 10.36 mg/l. Thus the policy is effective as far as the impact on water quality and net returns is concerned. But the effect of these changes on the stock of water is moderate compared to the base situation and thus we turn to options where both the quantity and quality of water are taken care of. The quota on water use restricts the amount of irrigation water use by 0.50 acre inches from the average use in the base run and also imposes the fertilizer use restriction. There is a 4% increase in the final stock of water as measured by the saturated thickness while nitrate stock falls by 2.82mg/l when compared to the base run. Again, a restriction on the terminal value of the saturated thickness to 50 feet is away to preserve the water stock to 60% of the initial reserve. As before water use falls on average to 6.90 acre inches /acre compared to the base value of 8.18acre inches /acre and the pollutant stock is 13.71 mg/l much lower than the base level accumulation of 17.07 mg/l. However, the two joint management policies lead to a loss of per acre NPV to the extent of $241.34 and $872 respectively. The buyout policy is an option for the irrigator to sell off her water rights by around 2 acre inches every year to the regulatory agency like the HPUWCD who in return compensates the irrigator. From the results for Castro County, it is found that when the buyout policy is combined with a restriction on the use of fertilizer, the fall in saturated thickness is around 6 feet lower than the corresponding fall in the base run while the pollutant stock rises by only 4 mg/l over the entire period. In addition, it leads to a gain in discounted net revenues of $14.07-$17.21 per acre on average from the base solution.

Lubbock

Apart from the policy of restricting the terminal value of saturated thickness, the same strategies as above are carried out for Lubbock County. The policies that are meant to control the use of fertilizer seem to have almost no impact on the stock of water, the input application rates and the pollutant level over the 20 year period. In fact, when the fertilizer use is restricted by around a pound per acre, the nitrate level goes down to 13.64 mg/ from the initial value of 21.02mg/l while the NPV per acre falls by around $104 from the base value. On the other hand, the quota on water use along with the restriction on fertilizer application achieves approximately 2 feet gain in saturated thickness but the tradeoff in discounted revenues is $72.59 per acre on average. Finally, the buyout policy benefits the producer in terms of NPV/ acre to an extent of $73.18 and again in saturated thickness of 3.31 feet relative to the base value at the end of the planning horizon.

Policy implications

Overall, the policies as implemented for Castro and Lubbock do show some variation as far as their impacts upon the water stock and the quality is concerned. For instance, the best management practice of restricting the polluting input leads to a $29 loss in NPV of production for Castro with a very favorable impact upon the nitrate stock at the end of the terminal year. For Lubbock the same leads to a $104 loss in NPV and is accompanied by a huge opportunity cost. Same is the case for the quota policy which again entails a loss in NPV of $998 /acre for Lubbock with minimal impact upon the nitrate stock. One probable reason might be differences in the nature of water quality and production practices currently in place for the two counties. Lubbock has switched to growing more cotton partly facilitated by the sandy soil and cotton being less water dependent. The water table is already shallow and the nitrate level as seen from the initial value is quite high to start off with. From the simulations done for the various policies, what is apparent is that the impact on the stock of water and the stock of pollutant is not so large and the only variable factor is the net revenues over the years. The fall in the pollutant stock over the years is actually an indication that regulations on the use of fertilizer may not be economically justified at least going by the results obtained in this study.

In addition, the question remains on how to impose an "endogenous" tax on the agents considering that the shadow prices on the constraint put on the fertilizer use could serve as the tax rates over the time period. On the other hand, the "exogenous" tax policy or the policy of raising the input price is more observable and easier to implement from the point of view of the regulator but is a direct disincentive to agents. The joint quantity-quality management policies like the quota on water use and the restriction on the terminal value of saturated thickness have positive impacts upon the stock of water and the stock of pollutant compared to the base solution for Castro, but unfavorable impacts on the discounted net revenues leave them open to policy debate in terms of implementation. Apart from the administrative costs of metering wells and keeping a check on the net annual pumping, they are likely to face the problems of economic feasibility and implementation. Limiting water use per acre is not an unusual practice but the rule of capture may intervene in translating the negotiations into reality. The quota on water use may be further affected by the possibility that water use beyond what has been stipulated by the regulatory agency needs to be taxed. As is well known in the environmental economics literature, a tax serves as a disincentive to users, though it is a good source of revenue for the Government. It then falls upon the regulator to make sure that the tax rate is not a deterrent to irrigated production and does not impose a high cost of bargaining on the two parties.

As far as the effect on discounted net revenues, stock of water conserved and the level of pollutant are concerned, the water rights buyout option offers the best strategy for policy makers seeking a long term objective. By purchasing water rights from the irrigator the regulatory agency ensures that the stock of water does not get exhausted in the near future. The virtue of such a policy is that the conservation incentives fall on the agent herself. There is an associated administrative cost of negotiations between the regulatory agency (say the HPUWCD) and the individual agent but this cost may be accepted as a regular environmental transaction cost. From a policy perspective it attains the joint management objective to a higher degree than all the policies considered. The notable aspect about the buyout of water rights is that it does not directly impose a pumping restriction on the user for maintaining the stock of water unlike the other two policies.

The water deeds approach on the lines advocated by Smith demonstrates the economics of groundwater trading using two representative farms of Castro County. The model examines the joint management of groundwater from a micro perspective. Two agents using the same inputs for production are allowed to trade after allocation of an initial set of permits for water extraction, with the agent having a higher initial stock selling groundwater permits to the one with lower level of water stock under her land. It is found that the transfer of a definite amount of water rights to the 'highest valued' user leads to lower level of input use, higher level of stocks held by each user and a favorable impact on the average pollution stock. Individual net revenues are compromised in the long run but to a much lesser extent for the purchaser of groundwater permits. Also, as established from the empirical results, permit trading has the potential to generate higher revenues while ensuring a stable use of the two inputs over time compared to a myopic model where any agent has limited foresight towards conservation. In a sense this model may be projected as equivalent to the buyout policy where any agent makes a tradeoff between her current water needs and net revenues through conservation incentives given by the regulator. One drawback however, in this model is the absence of trading relationship with an external agent; the dynamics of the groundwater stock depends upon the net purchase and sale every period. Nevertheless, the outcomes in terms of water quantity and quality and the water conservation incentives inherent in such a model is a step towards encouragement of more empirical studies on the working of groundwater markets in this region and may also be replicated for policy recommendations for other regions of Texas as well as through the country.

Limitations

Several limitations of the study crop up particularly in the way the model has been developed. First it does not account for any option of switching to dry land farming and hence there is possible overestimation in the values of saturated thickness over time. Though this will not have any impact in the main conclusions since the outcomes for the two counties have been generated with irrigated production, occurrence of dry land farming in any intervening years may be probable. The buyout of water rights may be reflective of such a situation.

Again a finite value for the irrigation return flow rate could affect the values of pumping lift and saturated thickness but due to lack of precise information on this return flow, it could not be incorporated it in the main modeling. A report published by TWDB (2003) on numerical simulations through 2050 for Texas and New Mexico, mentions a 10% irrigation return flow rate for Texas for the time period 1996-2000 but the time lag for the return flow may vary between 1 to 10 years.

Third, the imposition of any tax rate on an agent either through a rise in fertilizer price or through a limit on the use of fertilizer per acre or for violation of water use above a certain quota is uniform across agents since the individual agent behavior is unobservable or at least subject to costly monitoring. The lack of site specific data is one reason why a spatially differentiated tax rate has not been considered in this study. Also, the degradation rate of nitrate in the aquifer is held as a constant during the period of dynamic simulation. Depending upon changing physiological conditions in the aquifer, the degradation rate might change with the time period.

The study fails to take into account any change in technology using the center pivot with 90% efficiency as the standard measure of irrigation equipment used in all counties. A change in irrigation technology will affect the pumping costs and also the non pumping costs of production (the latter calculated from the projected figures in Enterprise Budget Sheet). The subsurface drip irrigation technique has been in practice in recent years but costs may get to be prohibitively high. However, a twenty year time horizon may not be too large to accommodate any change and its impact on the use of irrigation water and fertilizer. Moreover the basic applicability of the various policies explored should hold true and the numbers may change to some extent by introducing a different irrigation procedure.

The effect of increasing pollution on downstream users has not been investigated here, primarily due to the paucity of data and site specific characteristics. The research has broadly focused on the intertemporal consequences of agricultural use of groundwater and nitrogen fertilizer on the stock of water and pollutant. Increasing use of these two inputs add to the stock of pollutant but absence of a detailed hydrological assessment of the fate of the pollutant forbids any discussion on the impact on the groundwater quality or the marginal damage inflicted on users downstream.

Finally concerns remain about the aggregation of the data to county wide results. The simulations for each county were done with certain parameters denoting county level averages. For instance, the weather station is a single site and the weather parameters from this particular location are expected to hold for the whole county. Also, the predominant soil structure for each crop was taken as the representative soil for that crop grown in the county. It ignores the possibility that some specific area of a county may experience variation in the nature of the soil which may affect the absorption of the fertilizer and irrigation water. In short, there is a lack of site specific data in the main analysis.

Extensions

The study may be extended broadly on two fronts. One would be to explicitly incorporate a spatially disaggregated flow analysis into the modeling that can recover the exact nonpoint pollution effects that can help in refining the management strategies.

A possible extension to the agent based modeling would be to apply PMP techniques to calibrate farm level yield and cost parameters to historical values and then use the calibrated cost data to generate a farm level profit function. The marginal profit with respect to water use may then represent a value of marginal product curve for water or a farm level demand curve for water. The latter forms the basis of a farm level trading model as described in detail in Garrido (2000). Positive math programming (PMP) techniques have been employed for generating water demand schedules in studies done by Howitt (1995), Torell and Ward (2010) and Garrido (2000) among many others given its ability to replicate a more realistic farm level behavior. With some issues in historical levels of land use to be overcome, this is a direction for future research for the paper.

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APPENDIX A

A1: Let $Max \int_0^T \{[B(x_t\ , m_t) - C_t(S_t)x_t - P_m m_t]N_t\}e^{-rt}$ be the present valued Hamiltonian H

Let H_C be the current valued or the undiscounted Hamiltonian so that $H_C = He^{rt}$

or $$H = H_C e^{-rt}$$

Then our objective function looks like $H_C e^{-rt}$ subject to the given constraints

Let $\lambda_t^{'}$ b e the multiplier for the equation of motion for the water stock and $\mu_t^{'}$ be the multiplier for the equation of motion for the pollution stock. Then converting these two multipliers in the current valued form, we have:

or $$\lambda_t = \lambda_t^{'} e^{rt};\ \Lambda_t = \Lambda'_t e^{rt}$$

Then from the first order conditions:

or $$\lambda_t^{'} = -\frac{\delta H}{\delta S_t} \qquad \text{(A1.1)}$$

or $$\lambda_t e^{-rt} = \lambda_t^{'} \qquad \text{(A1.2)}$$

Similarly, $$\dot{\lambda} - r\lambda_t = -\frac{\delta H}{\delta S_t} \qquad \text{(A1.3)}$$

$$\dot{\Lambda}_t - r\Lambda_t = -\frac{\delta H}{\delta M_t} \qquad \text{(A1.4)}$$

A2:The differential equation for the co state variable λ_t is:

$$\dot{\lambda} - r\lambda_t = C'_t(S_t)N_t x_t \tag{A2.1}$$

Above is a linear first order differential equation with variable terms. Next we define the following:

$$C_s(t) = C'_t(S_t)N_t x_t \tag{A2.2}$$

$$\lambda_T = \lambda(T) \tag{A2.3}$$

Using definitions, differential equation may be written as:

$$\dot{\lambda} - r\lambda_t = C_s(t) \tag{A2.4}$$

Differential equation has the integrating factor e^{rt} and general solution

$$\lambda_t = e^{rt}(A + \int e^{-rt} C_s(t)\mathrm{dt} \tag{A2.5}$$

where, A is the constant of integration

Define $$F(t) = \int e^{-rt} C_s(t)dt$$

Above expression can be rewritten as

$$\lambda_t = e^{rt}(A + F(t)) \tag{A2.6}$$

$$\lambda_T = e^{rt}(A + F(T)) \tag{A2.7}$$

Where λ_T is found from the transversality condition defined above. Next we solve for A

$$A = e^{-rT}\lambda_T - F(T) \tag{A2.8}$$

Substituting the results back to the expression for λ_t

$$\lambda_t = e^{rt}[(e^{-rT}\lambda_T - F(T)) + F(t)] \tag{A2.9}$$

$$\lambda_t = e^{-r(T-t)}\lambda_T - e^{rt}[F(T) - F(t)] \tag{A2.10}$$

$$\lambda_t = e^{-r(T-t)}\lambda_T - e^{rt}\int_t^T e^{-r\tau}C_s(t)d\tau \tag{A2.11}$$

$$\lambda_t = e^{-r(T-t)}B_{ST}(S_T) - \int_t^T e^{-r(\tau-t)}C'_\tau(S_\tau)N_t x_\tau d\tau \tag{A2.12}$$

A3. $$log_e\Lambda_t = (r+\delta)t$$

or, $$\int d(\,log_e\Lambda_t) = \int (r+\delta)dt \tag{A3.1}$$

or, $$log_e\Lambda_t = (r+\delta)t + A \tag{A3.2}$$

where$A$ is the constant of integration.

At t=0, A=$log_e\Lambda_0$

$$log_e\Lambda_t = (r+\delta)t + log_e\Lambda_0 \tag{A3.3}$$

$$log_e\frac{\Lambda_t}{\Lambda_0} = (r+\delta)t \tag{A3.4}$$

or, $$\Lambda_t = e^{(r+\delta)t}\Lambda_0 \tag{A3.5}$$

A4: $$\dot{\Lambda}_t - (r+\delta)\Lambda_t = \theta_t\delta$$

The above is a linear first order differential equation with a variable term. Differential equation has an integrating factor $e^{(r+\delta)}$ and the general solution is:

$$\Lambda_t = e^{(r+\delta)t}(Z + \int e^{-(r+\delta)t}\,\theta_t \delta dt) \quad \text{(A4.1)}$$

where Z is the constant of integration.

Now we define G(t) as $$\text{G(t)}=\int e^{-(r+\delta)t}\,\theta_t \delta dt \quad \text{(A4.2)}$$

Therefore, $$\Lambda_t = e^{(r+\delta)t}[Z + \text{G(t)}] \quad \text{(A4.3)}$$

In terminal period T, $$\Lambda_T = e^{(r+\delta)T}[Z + G(T)] \quad \text{(A4.4)}$$

Where Λ_T is found from the transversality conditions. Next we solve for Z such that

$$Z = \Lambda_T e^{-(r+\delta)T} - G(T) \quad \text{(A4.5)}$$

Substituting back into Λ_t we get:

$$\Lambda_t = e^{(r+\delta)t}\{[\Lambda_T e^{-(r+\delta)T} - G(T)] + G(t)\} \quad \text{(A4.6)}$$

$$\Lambda_t = e^{-(r+\delta)(T-t)}\Lambda_T - e^{(r+\delta)t}[G(T) - G(t)] \quad \text{(A4.7)}$$

$$\Lambda_t = e^{-(r+\delta)(T-t)}\Lambda_T - e^{(r+\delta)t}\int_t^T e^{-(r+\delta)\tau}\,\theta_t \delta d\tau \quad \text{(A4.8)}$$

APPENDIX B

B1: Background information on water use and irrigated acreage

Table B1.1: Water use allocation

	Irrigation_GW	Irrigation_SW
BAILEY	161,030	0
CASTRO	501,219	0
HOCKLEY	197,497	0
LAMB	470,827	0
LUBBOCK	219,928	6,000
LYNN	105,698	5,000
PARMER	405,687	0
TERRY	98,195	0

Source: 2007 Water Use Survey Summary Estimates by county in acre-feet.GW: Groundwater SW: Surface water

Table B1.2: Irrigated crop acreage by county

	Wheat	Sorghum	Cotton	Corn
Bailey	61665.00	59245.24	92670.73	21665.00
Castro	127680.50	44792.86	60453.66	96284.21
Hockley	26078.05	76139.02	243834.10	
Lamb	54678.05	66438.10	89053.70	54034.00
Lubbock	27204.88	55902.38	266851.20	2859.09
Lynn	16253.66	42785.71	255968.3	
Parmer	127800.00	58302.38	129319.05	98140.48
Terry	24792.50	77592.86	243014.6	

Note: Figures denote average acres of irrigated cropland over the time period 1968-2009 as available from NASS. Observations are missing for some years for corn.

B2: Hydrologic and economic data used for optimization

Table B2.1: Hydrologic parameters for each county

	Saturated Thickness	Pumping lift	Area overlaying aquifer	Specific yield	eta	delta
	Feet	feet	acres			
Castro	79	233	574720	0.15	0.02	0.10
Parmer	73	305	564480	0.15	0.02	0.10
Bailey	62	111	529280	0.15	0.04	0.10
Hockley	39	133	581120	0.15	0.04	0.10
Lamb	64	167	650240	0.15	0.04	0.10
Lubbock	60	130	575360	0.15	0.05	0.10
Lynn	43	62	570880	0.15	0.06	0.10
Terry	47	94	569600	0.15	0.05	0.10

Source: Center for Geospatial Technology (2008).The values for delta are borrowed from the literature while those for eta are calculated by the procedure outlined in Fleming, Adams and Kim (2005).

Calculation of eta:

The parameter eta which represents the proportion of nitrogen percolating below the soil to the water is derived in the following manner. For each county the total nitrogen percolation from the simulated data was observed and an average of the observations taken. The average was then divided by the depth of the Ogallala in that county times the aquifer porosity or specific yield to obtain an approximate estimate of eta for that county. County specific soiltype provided differences in the values.

Table B2.2: Energy parameters

EF energy use factor for electricity	0.164
EP energy price/kw-hrs	0.09
EFF pump engine efficiency	0.50
PSI system operating pressure	16.50

Source: Wheeler (2008).

Table B2.3: Crop Prices and non pumping costs

	Corn ($/acre)	Cotton ($/acre)	Sorghum ($/acre)	Wheat ($/acre)
Crop prices[1]	3.89	0.56	3.47	5.69
Harvest cost	0.4	0.4	0.34	0.5
Labor cost	10	10	10	10
Maintenance cost	2	2	2	2
Operating cost	13.52	14.98	8.91	12.88
Fixed cost	40	40	40	40

Source: Food and Agricultural Policy Research Institute (FAPRI) projections 2007-2013.[1]The crop prices are respectively in $/bushel, $/pound, $/bushel and $/bushel.

B3: Parameters used for simulation

Table B3.1: Simulation data for counties

	Bailey	Castro	Hockley	Parmer	Lamb	Lubbock	Lynn	Terry
Dominant Soil	Amarillo (0-1%)	Pullman	Amarillo (0-1%)	Amarillo (0-1%)	Olton clay loam (0-1%)	Ota	Acuff (0-1%)	Amarillo (0-1%)
Irrigation system	Center Pivot (90%)	Center Pivot (90%)	Center Pivot (90%)	Center Pivot (90%)	Center Pivot (90%)	Center Pivot (90%)	Center Pivot (90%)	Center Pivot (90%)
Tillage	Reduced	Reduced	Reduced	Reduced	Reduced	Reduced	Reduced	Reduced
Fertilizer	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen
Weather station	Muleshoe	Dimmitt	Levelland	Friona	Littlefield	Lubbock	Tahoka	Plains

B4: Data Validation

Table B4.1: Actual and simulated yields for Castro County

Corn		Cotton		Wheat		Grain Sorghum	
Actual	Simulated	Actual	Simulated	Actual	Simulated	Actual	Simulated
172	188.84	955	899.59	38.5	45.06	83.8	59.52
195	183.57	1086	893.71	45.6	45.27	93.6	59.5
218	178.83	951	1043.76	46.2	45.36	58.3	55.52
204.6	177.57	818	852.78	68.4	45.25	106.2	55.51
201.5	166.34	1098	915.15	56.8	45.14	56.9	53.34
205.4	156.49	1080	1017.77	47.1	27.88	73.4	48.52
203	144.02	1254	1007.76	50	27.49	44.2	48.58
213	131.16			56	27.22	77	39.63
						75	38.74

Note: Actual yields correspond to NASS irrigated crop yield data (2001-2009). Data for 2008-09 are missing for some crops and hence the yields are reported for 2001-07. Simulated yields correspond to the average of yields obtained from the simulated observations under the conditions given in B3.

Table B4.2: Actual and simulated yields for Lubbock County

Cotton		Wheat		Grain Sorghum	
Actual	Simulated	Actual	Simulated	Actual	Simulated
731.775	447	19.77	36.7	85.03	47.3
734.05	600	42.72	31.3	81.14	42
734.05	605	27.12	33.3	62.09	52.8
917	852	27.99	20.2	63.33	37.1
855.4	954	27.65	34.6	39.02	70.9
855.4	727	27.58	28.9	28.17	75
688.15	1086	27.58	17	29.17	75
801.05	1046	27.67	42	29.17	72
		22.96	33.5	49.94	71

Note: Actual yields correspond to NASS irrigated crop yield data (2001-2009). Data for 2008-09 are missing for some crops and hence the yields are reported for 2001-07. Simulated yields correspond to the average of yields obtained from the simulated observations under the conditions given in B3.

Table B4.3: Mean yield from simulated and real data

Castro			Lubbock		
	Simulated	Real		Simulated	Real
Corn	158.96	183.2333			
Sorghum	50.99	83.4381	Sorghum	49.84	59.86
Cotton	947.21	795.0952	Cotton	789.61	624.23
Wheat	37.14	48.79091	Wheat	28.02	34.76

Note: Real data comes from NASS for the years 1987-2009.

Values hardly change when real data used for 1968-09 except for higher yield of cotton reported for 1987-09

B5: Gross Pumping Capacity Calculation

Hardin and Lacewell (1979, SJAE) derived a relationship between well yield (GPM) and saturated thickness (ST) of the aquifer as follows:

$$GPM = GPM_0 \ \ if \frac{ST}{250} \geq 0.83667$$

$$GPM = 1.14 * \left(\frac{ST}{250}\right)^{0.71} * GPM_0 \ if \ \frac{ST}{250} < 0.83667$$

The latter part can be used to calculate the well yield to derive a relationship between gross pumping capacity and saturated thickness in acre inches per acre. This is as follows:

$$GPC = 28.25 * \left(\frac{ST}{210}\right)^2$$

This corresponds to Feng's derivation (1992) taking an average well yield for 125 acres field.

$$GPM = 800\left(\frac{ST}{210}\right)^2$$

$$GPC = 0.03535GPM$$

$$GPC = 28.28 * \left(\frac{ST}{210}\right)^2$$

Weinheimer (2008): He used the relationship between GPM (gallons per minute) and saturated thickness given in Hardin(1973).

$$GPM = 2.264 * ST + 0.0078336 * ST^2 - 0.000282ST^3$$

However at given levels of saturated thickness the values of well yield in terms of GPM are lower than what was obtained in TWDB projections of 1974 for each county. His dynamic optimization is based on a per acre net revenue calculation like work done at Texas Tech. Also all of the research at Tech takes the gross pumping capacity formula as given by:

$$GPC = \left(4.42 * \frac{IWY}{IAcPer\ well}\right) * \left(\frac{ST}{IST}\right)^2$$

Where IWY is the initial well yield as obtained by the GM formula above, $IAcPer\ well$ is the quantity of acres per well, ST is the saturated thickness of aquifer at time t and IST is the initial saturated thickness of the aquifer. The average pumping hours per growing season is taken as 2000 hours.

B6: Results from estimations

Castro

Table B6.1: Estimated coefficients for different types of yield functions for corn based on simulated data

	Linear	Quadratic	Square root	Quadratic with interactions
IR	0.26	15.99	-32.90	
IR^2		-0.38	0.97	
N	1.00	0.48		
N^2		-0.00		
$IR^{1/2}$			279.04	
$N^{1/2}$			-20.81	
$(IR^* N)^{1/2}$			4.29	
IR*N		0.02		0.07***
$(IR^*N)^2$				-5.12e-06**
Cons	35.87	-120.78	-533.59	17.25

Note: IR- Irrigation water N- nitrogen.. "*" ,"**" & "***" denote 10%, 5% and 1% level of significance respectively.

Table B6.2Estimated coefficients for different types of yield functions for grain sorghum based on simulated data

	Linear	Quadratic	Square root	Quadratic with interactions
IR	-1.299	-41.49	-337.80	
IR^2		-4.19		
N	-0.91*	7.11	-82 .26	
N^2		- 0.17		
$IR^{1/2}$			-697.97	
$N^{1/2}$			391.39	
$(IR* N)^{1/2}$			329.92	
IR*N		1.65		0.045 ***
$(IR*N)^2$				-0.00000642**
Cons	10.19	-147.41	-612.08	28.94**

Note: IR- Irrigation water N- nitrogen. "*" ,"**" & "***" denote 10%, 5% and 1% level of significance respectively.

Table B6.3: Estimated coefficients for different types of yield functions for cotton based on simulated data

	Linear	Quadratic	Square root	Quadratic with interactions
IR	45.66***	58.37	-43.95	
IR^2		-2.09		
N	-0.09	-2.92	-4.16	
N^2		-0.01		
$IR^{1/2}$			154.35	
$N^{1/2}$			-98.65	
$(IR^* N)^{1/2}$			49.20	
IR*N		0.42		0.79*
IR^*N^2				-0.0002
Cons	503.86	528.90	690.23	530.68

Note: IR- Irrigation water N- nitrogen. .“*” ,“**” & “***” denote 10%, 5% and 1% level of significance respectively.

Table B6.4: Estimated coefficients for different types of yield functions for wheat based on simulated data

	Linear	Quadratic	Square root	Quadratic with interactions
IR	0.61	-28.97	-26.65	
IR^2		-1.37		
N	-0.08	3.74	-9.73	
N^2		-0.03		
$IR^{1/2}$			-222.06	
$N^{1/2}$			108.61	
$(IR^* N)^{1/2}$			34.82	
IR*N		0.44		0.006
IR^*N^2				-0.0000025
Cons	21.39	-75.88	-243.29	13.22

Note: IR- Irrigation water N- nitrogen. .“*” ,“**” & “***” denote 10%, 5% and 1% level of significance respectively.

Table B6.5: Estimated coefficients for different types of leaching functions for corn based on simulated data

	Linear	Linear with interactions	Tobit
PRK	0.079***	0.07***	0.20***
CRF	-0.002		0.009
GYLD	-0.0007***	-0.0007**	-0.007
TNO3	-0.0004	0.00	-0.004
IR	-0.003	-0.02	-0.029
N	0.002***	-0.00	0.011
IR*N		0.00	
IR* TNO3		-0.00	
Cons	-0.02	0.36	-0.04

Note: IR- Irrigation water N- nitrogen PRK- Percolation below the root zone CRF-Growing season precipitation GYLD-Grain Yield TNO3- Soil nitrogen. The marginal effects are reported for Tobit. "*" ,"**" & "***" denote 10%, 5% and 1% level of significance respectively.

Table B6.6: Estimated coefficients for different types of leaching functions for grain sorghum based on simulated data

	Linear	Linear with interactions
PRK	0.23***	0.39***
CRF	1.03***	
GYLD	-0.26***	-0.21***
TNO3	-0.89 ***	1.32
IR	0.23**	-0.97
N	0.71**	0.58*
IR*N		0.01
IR* TNO3		-0.15**
Cons	-11.09	8.39

Note: IR- Irrigation waterN- nitrogen PRK- Percolation below the root zone CRF-Growing season precipitation GYLD-Grain Yield TNO3- Soil nitrogen. "*" ,"**" & "***" denote 10%, 5% and 1% level of significance respectively.

Table B6.7: Estimated coefficients for different types of leaching functions for cotton based on simulated data

	Linear	Linear with interactions	Tobit
PRK	19.48***	20.43***	31.18***
CRF	-1.24**	-1.24**	-5.77***
GYLD	0.03***	0.03***	0.12***
TNO3	-0.04***	-0.08***	-0.06**
IR	-10.19***	-25.33***	-17.28***
N	1.38***	-1.56	2.09***
IR*N		0.22**	
IR* TNO3		0.007**	
Cons	27.61	-99.63	1.91

Note: IR- Irrigation water N- nitrogen PRK- Percolation below the root zone CRF-Growing season precipitation GYLD-Grain Yield TNO3- Soil nitrogen. The marginal effects are reported for Tobit. "*" ,"**" & "***" denote 10%, 5% and 1% level of significance respectively.

Table B6.8: Estimated coefficients for different types of leaching functions for wheat based on simulated data

	Linear	Linear with interactions
PRK	1.76***	1.04***
CRF	-4.92***	
GYLD	-2.27***	-2.60***
TNO3	-0.22***	-0.09
IR	-13.62***	-22.11
N	1.29***	-1.44
IR*N		0.19
IR* TNO3		-0.05**
Cons	47.47	288.56

Note: IR- Irrigation water N- nitrogen PRK- Percolation below the root zone CRF-Growing season precipitation GYLD-Grain Yield TNO3- Soil nitrogen. "*" ,"**" & "***" denote 10%, 5% and 1% level of significance respectively.

Lubbock estimates

Table B6.9: Estimated coefficients for different types of yield functions for grain sorghum based on simulated data

	Linear	Quadratic	Square root	Quadratic with interactions
IR	3.79***	-19.05*	-2.97	
IR^2		-1.02**		
N	-0.41**	2.83	- 1.69	
N^2		- 0.02*		
$IR^{1/2}$			-79.05	
$N^{1/2}$			24.56	
$(IR^* N)^{1/2}$			9.84	
IR*N		0.28**		0.054 ***
$(IR^*N)^2$				-0.00000834**
Cons	-22.85*	-104.06	- 68.83	14.69***

Note: IR- Irrigation water N- nitrogen. "*" ,"**" & "***" denote 10%, 5% and 1% level of significance respectively.

Table B6.10: Estimated coefficients for different types of yield functions for cotton based on simulated data

	Linear	Quadratic	Square root	Quadratic with interactions
IR	14.62*	136.15		
IR^2		-1.31		
N	-2.76	83.15**		
N^2		-0.54*		
$IR^{1/2}$				
$N^{1/2}$				
$(IR*N)^{1/2}$				
IR*N		-1.65		0.17*
$IR*N^2$				-0.0000059
Cons	939.81***	-2403.58		741.42***

Note: IR- Irrigation water N- nitrogen. .“*” ,“**” & “***” denote 10%, 5% and 1% level of significance respectively.

Table B6.11: Estimated coefficients for different types of yield functions for wheat based on simulated data

	Linear	Quadratic	Square root	Quadratic with interactions
IR	- 3.16*	-284.90	-614.48***	
IR^2		-25.81***		
N	0.44*	36.02***	-119.33**	
N^2		-0.41***		
$IR^{1/2}$			-2131.60**	
$N^{1/2}$			948.16**	
$(IR^* N)^{1/2}$			540.60**	
IR*N		6.51***		0.02**
IR^*N^2				-0.00000836**
Cons	5.21	-766.09***	-1879.42*	17.24***

Note: IR- Irrigation water N- nitrogen. .“*” ,“**” & “***” denote 10%, 5% and 1% level of significance respectively.

Table B6.12: Estimated coefficients for different types of leaching functions for grain sorghum based on simulated data

	Linear	Linear with interactions	Tobit
PRK	1.95***	1.87***	2.57***
CRF	-1.36**		-1.49*
GYLD	0.28**	0.12	0.58***
TNO3	0.06 ***	0.05***	0.08***
IR	6.61***	9.75*	5.76***
N	-1.16***	-0.77**	-1.11***
IR*N		-0.04	
IR* TNO3		0.00	
Cons	48.69**	-2.35	-25.59

Note: IR- Irrigation water N- nitrogen PRK- Percolation below the root zone CRF-Growing season precipitation GYLD-Grain Yield TNO3- Soil nitrogen. The marginal effects are reported for Tobit. "*" ,"**" & "***" denote 10%, 5% and 1% level of significance respectively.

Table B6.13: Estimated coefficients for different types of leaching functions for cotton based on simulated data

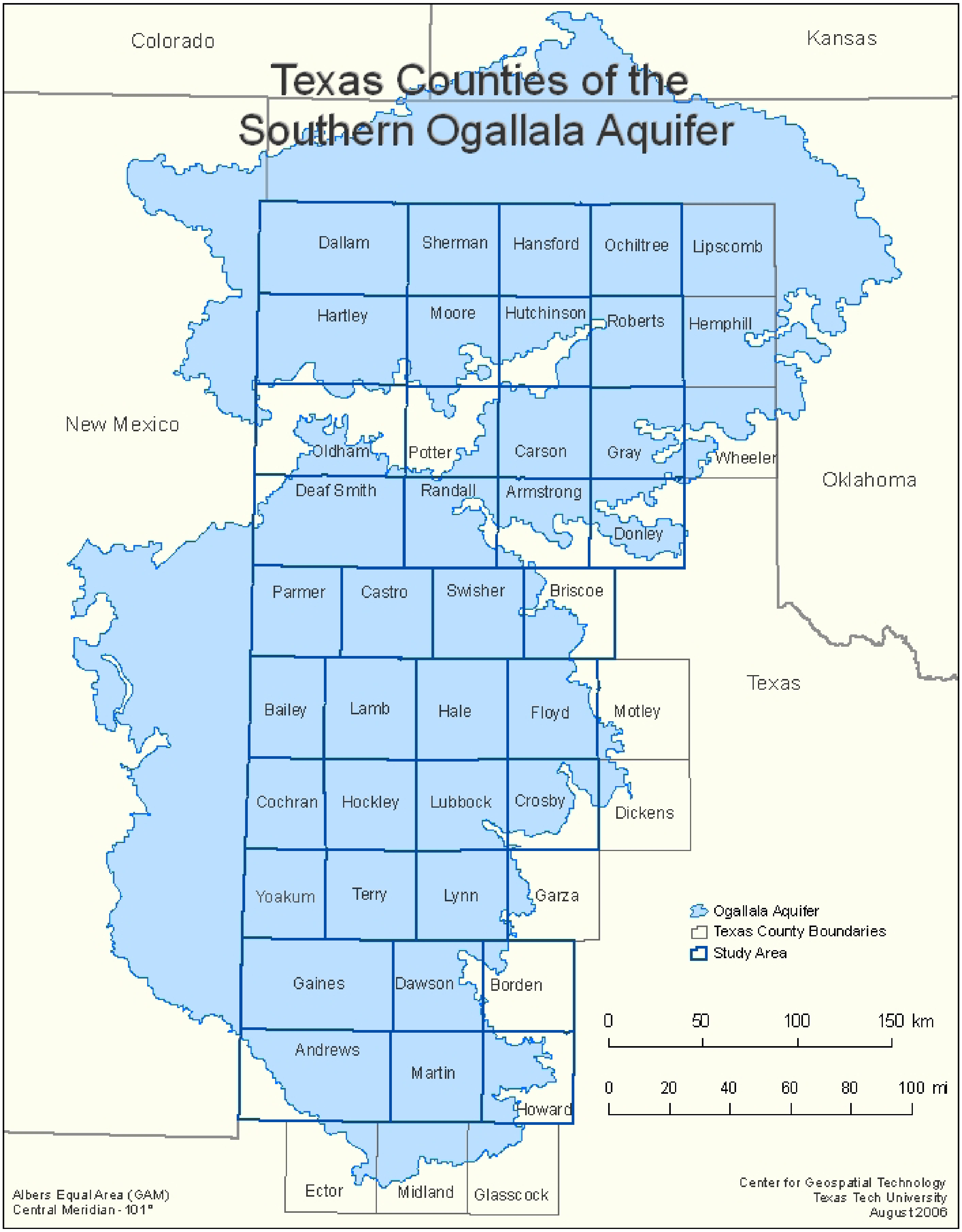
	Linear	Linear with interactions	Tobit
PRK	1.39***	1.09***	1.69***
CRF	-0.68**		-0.79*
GYLD	0.009*	-0.009***	0.02**
TNO3	0.09***	0.64**	0.11***
IR	1.82***	2.86	1.70**
N	-0.26*	1.09	-0.26
IR*N		-0.04	
IR* TNO3		-0.11**	
Cons	-39.30	- 42.71	-78.55***

Note: IR- Irrigation waterN- nitrogen PRK- Percolation below the root zone CRF-Growing season precipitation GYLD-Grain Yield TNO3- Soil nitrogen. The marginal effects are reported for Tobit. “*” ,“**” & “***” denote 10%, 5% and 1% level of significance respectively.

Table B6.14: Estimated coefficients for different types of leaching functions for wheat based on simulated data

	Linear	Linear with interactions
PRK	0.81***	0.67***
CRF	-2.33***	
GYLD	-1.41***	-1.57***
TNO3	-0.31***	-0.77***
IR	-19.62***	3.15
N	2.99***	3.77***
IR*N		-0.16***
IR* TNO3		0.03*
Cons	-24.24	-132.55***

Note: IR- Irrigation water N- nitrogen PRK- Percolation below the root zone CRF-Growing season precipitation GYLD-Grain Yield TNO3- Soil nitrogen. "*" ,"**" & "***" denote 10%, 5% and 1% level of significance respectively.


Texas Counties of the
Southern Ogallala Aquifer
Colorado
Kansas
New Mexico
Oklahoma
Texas
Dallam
Sherman
Hansford
Ochiltree
Lipscomb
Hartley
Moore
Hutchinson
Roberts
Hemphill
Oldham
Potter
Carson
Gray
Wheeler
Deaf Smith
Randall
Armstrong
Donley
Parmer
Castro
Swisher
Briscoe
Bailey
Lamb
Hale
Floyd
Motley
Cochran
Hockley
Lubbock
Crosby
Dickens
Yoakum
Terry
Lynn
Garza
Gaines
Dawson
Borden
Andrews
Martin
Howard
Ector
Midland
Glasscock
Ogallala Aquifer
Texas County Boundaries
Study Area
0 50 100 150 km
0 20 40 60 80 100 mi
Albers Equal Area (GAM)
Central Meridian - 101°
Center for Geospatial Technology
Texas Tech University
August 2006

APPENDIX C

CASTRO

Table C.1: Base Run

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discounted NR $/acre
1	8.19	158.52	92.57	6.37	79.00	233.00	5.46	477.76
2	8.19	158.57	92.71	7.58	77.08	234.92	5.50	477.31
3	8.19	158.62	92.83	8.68	75.17	236.83	5.54	476.87
4	8.19	158.66	92.95	9.67	73.28	238.72	5.58	476.44
5	8.19	158.70	93.07	10.56	71.39	240.61	5.61	476.00
6	8.19	158.74	93.18	11.37	69.51	242.49	5.65	475.57
7	8.18	158.78	93.29	12.09	67.64	244.36	5.69	475.14
8	8.18	158.82	93.39	12.75	65.78	246.22	5.72	474.71
9	8.18	158.85	93.48	13.34	63.94	248.06	5.76	474.28
10	8.18	158.89	93.57	13.88	62.10	249.90	5.80	473.86
11	8.18	158.91	93.63	14.36	60.27	251.73	5.83	473.44
12	8.18	158.94	93.72	14.80	58.47	253.53	5.87	473.02
13	8.18	158.96	93.77	15.19	56.66	255.34	5.90	472.61
14	8.18	158.98	93.83	15.55	54.88	257.12	5.94	472.20
15	8.18	159.00	93.88	15.87	53.11	258.89	5.97	471.79
16	8.18	159.02	93.92	16.16	51.35	260.65	6.01	471.39
17	8.18	159.03	93.96	16.42	49.60	262.40	6.04	470.98
18	8.17	159.04	93.99	16.66	47.84	264.16	6.08	470.58
19	8.17	159.05	94.01	16.87	46.09	265.92	6.11	470.18
20	8.17	159.05	94.02	17.07	44.34	267.66	6.15	469.78

Note: *Irr*represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch, and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $6517/acre

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Table C.2: Nitrogen fertilizer price raised to $0.53/lb

years	irr	fert	percolation	nitconc	satthickness	plift	pcost	discounted NR
	ac-in/acre	llbs/acre	lbs/acre	ıg/liter	feet	feet	$/ac-in	$/acre
1	8.24	156.70	88.00	6.37	79.00	233.00	5.49	473.28
2	8.24	156.75	88.13	7.49	77.07	234.93	5.53	472.84
3	8.24	156.80	88.26	8.51	75.15	236.85	5.57	472.39
4	8.23	156.84	88.38	9.42	73.24	238.76	5.61	471.95
5	8.23	156.88	88.49	10.25	71.35	240.65	5.65	471.51
6	8.23	156.92	88.60	10.99	69.46	242.54	5.68	471.07
7	8.23	156.96	88.71	11.67	67.58	244.42	5.72	470.63
8	8.23	156.99	88.80	12.27	65.71	246.29	5.76	470.20
9	8.23	157.03	88.90	12.82	63.85	248.15	5.79	469.77
10	8.23	157.06	88.98	13.32	62.00	250.00	5.83	469.34
11	8.23	157.08	89.04	13.77	60.16	251.84	5.87	468.92
12	8.22	157.11	89.13	14.17	58.35	253.65	5.90	468.50
13	8.22	157.13	89.18	14.54	56.53	255.47	5.94	468.08
14	8.22	157.15	89.24	14.87	54.74	257.26	5.97	467.66
15	8.22	157.17	89.29	15.16	52.96	259.04	6.01	467.25
16	8.22	157.19	89.33	15.43	51.19	260.81	6.05	466.84
17	8.22	157.20	89.37	15.68	49.43	262.57	6.08	466.43
18	8.22	157.21	89.40	15.90	47.66	264.34	6.12	466.03
19	8.22	157.22	89.42	16.09	45.90	266.10	6.15	465.62
20	8.22	157.22	89.43	16.27	44.15	267.85	6.19	465.21

Note: *Irr*represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch, and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $6455.62/acre

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Table C.3: Nitrogen fertilizer price raised to $0.55/lb

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discounted NR $/acre
1	8.27	155.58	85.14	6.37	79.00	233.00	5.51	470.33
2	8.27	155.62	85.27	7.44	77.06	234.94	5.55	469.88
3	8.27	155.67	85.40	8.40	75.14	236.86	5.59	469.43
4	8.26	155.71	85.52	9.27	73.22	238.78	5.63	468.98
5	8.26	155.75	85.63	10.05	71.32	240.68	5.67	468.54
6	8.26	155.79	85.74	10.76	69.42	242.58	5.70	468.10
7	8.26	155.83	85.84	11.40	67.54	244.46	5.74	467.66
8	8.26	155.86	85.94	11.97	65.66	246.34	5.78	467.22
9	8.26	155.89	86.03	12.50	63.80	248.20	5.82	466.79
10	8.26	155.92	86.11	12.97	61.94	250.06	5.85	466.36
11	8.25	155.95	86.17	13.39	60.10	251.91	5.89	465.93
12	8.25	155.98	86.26	13.78	58.28	253.72	5.93	465.51
13	8.25	156.00	86.31	14.12	56.45	255.55	5.96	465.08
14	8.25	156.02	86.37	14.44	54.66	257.34	6.00	464.67
15	8.25	156.03	86.42	14.72	52.87	259.13	6.03	464.25
16	8.25	156.05	86.46	14.98	51.09	260.91	6.07	463.84
17	8.25	156.06	86.50	15.21	49.32	262.68	6.10	463.43
18	8.25	156.07	86.53	15.42	47.55	264.45	6.14	463.02
19	8.25	156.08	86.55	15.61	45.78	266.22	6.18	462.61
20	8.25	156.08	86.56	15.78	44.02	267.98	6.21	462.20

Note: *Irr*represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch, and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $6414.68/acre

Table C.4: Nitrogen fertilizer application limited to 144lbs/acre

years	irr ac-in/acre	fert lbs/acre	shadow prices $/lb	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discounted NR $/acre
1	8.64	144.00	0.34	54.76	6.37	79.00	233.00	5.76	476.00
2	8.64	144.00	0.33	54.78	6.83	76.98	235.02	5.81	475.51
3	8.64	144.00	0.31	54.79	7.24	74.96	237.04	5.85	475.02
4	8.64	144.00	0.30	54.81	7.61	72.96	239.04	5.89	474.53
5	8.64	144.00	0.28	54.83	7.95	70.97	241.03	5.93	474.05
6	8.64	144.00	0.27	54.84	8.25	68.99	243.01	5.97	473.57
7	8.64	144.00	0.26	54.86	8.52	67.01	244.99	6.02	473.09
8	8.64	144.00	0.25	54.87	8.77	65.05	246.95	6.06	472.61
9	8.64	144.00	0.24	54.89	8.99	63.10	248.90	6.10	472.14
10	8.64	144.00	0.23	54.90	9.19	61.16	250.84	6.14	471.67
11	8.64	144.00	0.22	54.91	9.37	59.23	252.77	6.18	471.20
12	8.64	144.00	0.21	54.92	9.53	57.33	254.67	6.22	470.74
13	8.64	144.00	0.20	54.93	9.67	55.42	256.58	6.26	470.27
14	8.64	144.00	0.19	54.94	9.80	53.54	258.46	6.30	469.82
15	8.63	144.00	0.18	54.94	9.92	51.67	260.33	6.34	469.36
16	8.63	144.00	0.17	54.95	10.03	49.81	262.19	6.38	468.91
17	8.63	144.00	0.16	54.96	10.13	47.96	264.04	6.42	468.46
18	8.63	144.00	0.16	54.96	10.21	46.10	265.90	6.46	468.01
19	8.63	144.00	0.15	54.96	10.29	44.25	267.75	6.50	467.56
20	8.63	144.00	0.14	54.97	10.36	42.41	269.59	6.54	467.11

Note*Irr* = amount of irrigation water applied per acre, *fert* = amount of nitrogen fertilizer applied per acre, *percolation* = amount of fertilizer that percolates below the root zone, *nitconc* = level of nitrate in the water, *satthickness* = saturated thickness of the aquifer, *plift* = pumping lift of the aquifer, *pcost* = pumping cost per acre and *discounted NR* = discounted value of net revenues over the years from this activity.

NPV: $6488.24/acre

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Table C.5: Irrigation water use restricted to 0.50 acre inches less per acre from the average base value along with a restriction on fertilizer use

years	irr	fert	percolation	nitconc	satthickness	plift	pcost	discounted NR
	ac-in/acre	lbs/acre	lbs/acre	mg/liter	feet	feet	$/ac-in	$/acre
1	7.68	144.00	77.37	6.37	79.00	233.00	5.12	459.74
2	7.68	144.00	77.37	7.28	77.20	234.80	5.16	459.35
3	7.68	144.00	77.37	8.10	75.41	236.59	5.19	458.96
4	7.68	144.00	77.37	8.84	73.63	238.37	5.22	458.58
5	7.68	144.00	77.37	9.50	71.86	240.14	5.26	458.20
6	7.68	144.00	77.37	10.10	70.10	241.90	5.29	457.82
7	7.68	144.00	77.37	10.64	68.35	243.65	5.32	457.44
8	7.68	144.00	77.37	11.12	66.60	245.40	5.36	457.06
9	7.68	144.00	77.37	11.56	64.87	247.13	5.39	456.69
10	7.68	144.00	77.37	11.95	63.14	248.86	5.42	456.31
11	7.68	144.00	77.37	12.30	61.43	250.57	5.45	455.94
12	7.68	144.00	77.37	12.62	59.74	252.26	5.49	455.58
13	7.68	144.00	77.37	12.90	58.04	253.96	5.52	455.21
14	7.68	144.00	77.37	13.16	56.37	255.64	5.55	454.85
15	7.68	144.00	77.37	13.39	54.70	257.30	5.58	454.49
16	7.68	144.00	77.37	13.60	53.05	258.95	5.61	454.14
17	7.68	144.00	77.37	13.79	51.40	260.60	5.64	453.79
18	7.68	144.00	77.37	13.96	49.75	262.25	5.67	453.42
19	7.68	144.00	77.37	14.11	48.10	263.90	5.71	453.05
20	7.68	144.00	77.37	14.25	46.47	265.53	5.74	452.70

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch, and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $6275.66/acre

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Table C.6: Saturated thickness level restricted to 50 feet at the end of the terminal period

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discounted NR $/acre
1	7.19	135.00	74.19	6.37	79.00	233.00	4.80	433.91
2	7.19	135.00	74.19	7.22	77.32	234.68	4.83	433.57
3	7.19	135.00	74.19	7.98	75.64	236.36	4.86	433.23
4	7.19	135.00	74.19	8.67	73.97	238.03	4.89	432.89
5	7.19	135.00	74.19	9.28	72.32	239.69	4.92	432.56
6	7.19	135.00	74.19	9.84	70.67	241.34	4.94	432.22
7	7.19	135.00	74.19	10.34	69.02	242.98	4.97	431.89
8	7.19	135.00	74.19	10.79	67.39	244.61	5.00	431.56
9	7.19	135.00	74.19	11.19	65.77	246.24	5.03	431.23
10	7.19	135.00	74.19	11.56	64.15	247.85	5.06	430.90
11	7.19	135.00	74.19	11.89	62.54	249.46	5.09	430.58
12	7.08	135.00	74.20	12.18	60.96	251.04	5.03	421.16
13	6.93	135.00	74.22	12.45	59.39	252.61	4.96	408.86
14	6.73	135.00	74.24	12.69	57.88	254.12	4.84	391.48
15	6.52	135.00	74.26	12.90	56.43	255.58	4.71	372.59
16	6.30	135.00	74.29	13.10	55.02	256.98	4.57	352.07
17	6.01	135.00	74.32	13.27	53.67	258.33	4.38	323.82
18	5.72	135.00	74.38	13.43	52.38	259.62	4.19	293.97
19	5.41	135.00	74.45	13.58	51.15	260.85	3.98	261.50
20	8.19	135.00	48.32	13.71	50.00	262.00	6.05	456.70

Note: *Irr*represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch, and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $5645.08/acre.

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Table C.7: Sale of water rights by around 2 acre inches per acre per year with fertilizer use restriction

years	irr	fert	percolation	nitconc	satthickness	plift	pcost	discounted NR
	ac-in/acre	lbs/acre	lbs/acre	mg/liter	feet	feet	$/ac-in	$/acre
1	6.65	144.00	54.66	6.37	79.00	233.00	4.43	491.82
2	6.65	144.00	54.68	6.83	77.44	234.56	4.46	491.53
3	6.65	144.00	54.69	7.24	75.90	236.11	4.48	491.24
4	6.65	144.00	54.70	7.61	74.36	237.65	4.51	490.95
5	6.65	144.00	54.72	7.94	72.82	239.18	4.53	490.67
6	6.65	144.00	54.73	8.24	71.30	240.70	4.56	490.38
7	6.64	144.00	54.74	8.51	69.78	242.22	4.58	490.10
8	6.64	144.00	54.75	8.76	68.27	243.73	4.61	489.82
9	6.64	144.00	54.76	8.97	66.77	245.23	4.63	489.54
10	6.64	144.00	54.77	9.17	65.28	246.72	4.65	489.26
11	6.64	144.00	54.78	9.35	63.79	248.21	4.68	488.98
12	6.64	144.00	54.79	9.51	62.33	249.67	4.70	488.71
13	6.64	144.00	54.79	9.66	60.86	251.14	4.73	488.43
14	6.64	144.00	54.80	9.79	59.42	252.58	4.75	488.14
15	6.64	144.00	54.81	9.90	57.98	254.02	4.77	487.80
16	6.64	144.00	54.81	10.01	56.55	255.45	4.80	487.43
17	6.64	144.00	54.81	10.10	55.13	256.88	4.82	487.07
18	6.64	144.00	54.82	10.19	53.70	258.31	4.84	487.09
19	6.64	144.00	54.82	10.27	52.27	259.73	4.87	487.25
20	6.64	144.00	54.82	10.34	50.86	261.14	4.89	486.98

Note: *Irr*represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch, and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $6726.82/acre

Table C.8: Discounted net revenues under the different policies

years	base $/acre	nitp_0.53 $/acre	nitp_0.55 $/acre	constraint $/acre	quota $/acre	satt_50 $/acre	buyout $/acre
1	477.76	473.28	470.33	476.00	459.74	433.91	491.82
2	477.31	472.84	469.88	475.51	459.35	433.57	491.53
3	476.87	472.39	469.43	475.02	458.96	433.23	491.24
4	476.44	471.95	468.98	474.53	458.58	432.89	490.95
5	476.00	471.51	468.54	474.05	458.20	432.56	490.67
6	475.57	471.07	468.10	473.57	457.82	432.22	490.38
7	475.14	470.63	467.66	473.09	457.44	431.89	490.10
8	474.71	470.20	467.22	472.61	457.06	431.56	489.82
9	474.28	469.77	466.79	472.14	456.69	431.23	489.54
10	473.86	469.34	466.36	471.67	456.31	430.90	489.26
11	473.44	468.92	465.93	471.20	455.94	430.58	488.98
12	473.02	468.50	465.51	470.74	455.58	421.16	488.71
13	472.61	468.08	465.08	470.27	455.21	408.86	488.43
14	472.20	467.66	464.67	469.82	454.85	391.48	488.14
15	471.79	467.25	464.25	469.36	454.49	372.59	487.80
16	471.39	466.84	463.84	468.91	454.14	352.07	487.43
17	470.98	466.43	463.43	468.46	453.79	323.82	487.07
18	470.58	466.03	463.02	468.01	453.42	293.97	487.09
19	470.18	465.62	462.61	467.56	453.05	261.50	487.25
20	469.78	465.21	462.20	467.11	452.70	456.70	486.98

Note:*nitp_0.53* and *nitp_0.55* refer to price of fertilizer being raised by 5% and 10% respectively.*Constraint* refers to the restriction on fertilizer use by 144 lbs per acre, *quota* denotes the restriction of irrigation water use by $0.50 per acre inch from the average base value. *satt_50* refers to the saturated thickness being restricted to 50 feet at the end of the terminal period, while *buyout* denotes the purchase of water rights by around 2 acre inches per acre by the Groundwater Conservation District.

Table C.9: Nitrate concentration levels under the different policies

years	base mg/liter	nitp_0.52 mg/liter	nitp_0.55 mg/liter	constraint mg/liter	quota mg/liter	satt_50 mg/liter	buyout mg/liter
1	6.37	6.37	6.37	6.37	6.37	6.37	6.37
2	7.58	7.49	7.44	6.83	7.28	7.22	6.83
3	8.68	8.51	8.40	7.24	8.10	7.98	7.24
4	9.67	9.42	9.27	7.61	8.84	8.67	7.61
5	10.56	10.25	10.05	7.95	9.50	9.28	7.94
6	11.37	10.99	10.76	8.25	10.10	9.84	8.24
7	12.09	11.67	11.40	8.52	10.64	10.34	8.51
8	12.75	12.27	11.97	8.77	11.12	10.79	8.76
9	13.34	12.82	12.50	8.99	11.56	11.19	8.97
10	13.88	13.32	12.97	9.19	11.95	11.56	9.17
11	14.36	13.77	13.39	9.37	12.30	11.89	9.35
12	14.80	14.17	13.78	9.53	12.62	12.18	9.51
13	15.19	14.54	14.12	9.67	12.90	12.45	9.66
14	15.55	14.87	14.44	9.80	13.16	12.69	9.79
15	15.87	15.16	14.72	9.92	13.39	12.90	9.90
16	16.16	15.43	14.98	10.03	13.60	13.10	10.01
17	16.42	15.68	15.21	10.13	13.79	13.27	10.10
18	16.66	15.90	15.42	10.21	13.96	13.43	10.19
19	16.87	16.09	15.61	10.29	14.11	13.58	10.27
20	17.07	16.27	15.78	10.36	14.25	13.71	10.34

Note*: nitp_0.53* and *nitp_0.55* refer to price of fertilizer being raised by 5% and 10% respectively. *Constraint* refers to the restriction on fertilizer use by 144 lbs per acre, *quota* denotes the restriction of irrigation water use by $0.50 per acre inch from the average base value. *satt_50* refers to the saturated thickness being restricted to 50 feet at the end of the terminal period, while *buyout* denotes the purchase of water rights by around 2 acre inches per acre by the Groundwater Conservation District.

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Table C.10: Base Run

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discountedNR $/acre
1	3.82	67.93	27.58	21.02	60.00	130.00	1.58	218.87
2	3.82	67.93	27.58	20.30	59.38	130.62	1.59	218.80
3	3.82	67.93	27.58	19.65	58.75	131.25	1.59	218.74
4	3.82	67.93	27.58	19.06	58.12	131.88	1.60	218.67
5	3.82	67.93	27.58	18.53	57.48	132.52	1.60	218.60
6	3.82	67.93	27.58	18.06	56.83	133.17	1.61	218.53
7	3.82	67.93	27.58	17.63	56.17	133.83	1.62	218.46
8	3.82	67.93	27.58	17.25	55.50	134.50	1.62	218.39
9	3.82	67.93	27.58	16.90	54.83	135.17	1.63	218.31
10	3.82	67.93	27.58	16.59	54.15	135.85	1.64	218.24
11	3.82	67.93	27.58	16.31	53.46	136.54	1.64	218.17
12	3.82	67.93	27.58	16.06	52.76	137.24	1.65	218.09
13	3.82	67.93	27.58	15.83	52.07	137.93	1.66	218.02
14	3.82	67.93	27.58	15.63	51.38	138.62	1.66	217.94
15	3.82	67.93	27.58	15.44	50.69	139.31	1.67	217.87
16	3.82	67.93	27.58	15.28	50.01	139.99	1.68	217.80
17	3.82	67.93	27.58	15.13	49.33	140.67	1.68	217.72
18	3.82	67.93	27.58	14.99	48.66	141.34	1.69	217.65
19	3.82	67.93	27.58	14.87	48.00	142.00	1.69	217.58
20	3.82	67.93	27.58	14.77	47.35	142.65	1.70	217.51

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $2999.53/acre

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Table C.11: Nitrogen fertilizer price raised to 0.53/lb

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discountedNR $/acre
1	3.82	67.93	27.58	21.02	60.00	130.00	1.58	216.93
2	3.82	67.93	27.58	20.30	59.38	130.62	1.59	216.86
3	3.82	67.93	27.58	19.65	58.75	131.25	1.59	216.80
4	3.82	67.93	27.58	19.06	58.12	131.88	1.60	216.73
5	3.82	67.93	27.58	18.53	57.48	132.52	1.60	216.66
6	3.82	67.93	27.58	18.06	56.83	133.17	1.61	216.59
7	3.82	67.93	27.58	17.63	56.17	133.83	1.62	216.52
8	3.82	67.93	27.58	17.25	55.50	134.50	1.62	216.45
9	3.82	67.93	27.58	16.90	54.83	135.17	1.63	216.37
10	3.82	67.93	27.58	16.59	54.15	135.85	1.64	216.30
11	3.82	67.93	27.58	16.31	53.46	136.54	1.64	216.23
12	3.82	67.93	27.58	16.06	52.76	137.24	1.65	216.15
13	3.82	67.93	27.58	15.83	52.07	137.93	1.66	216.08
14	3.82	67.93	27.58	15.63	51.38	138.62	1.66	216.00
15	3.82	67.93	27.58	15.44	50.69	139.31	1.67	215.93
16	3.82	67.93	27.58	15.28	50.01	139.99	1.68	215.86
17	3.82	67.93	27.58	15.13	49.33	140.67	1.68	215.78
18	3.82	67.93	27.58	14.99	48.66	141.34	1.69	215.71
19	3.82	67.93	27.58	14.87	48.00	142.00	1.69	215.64
20	3.82	67.93	27.58	14.77	47.35	142.65	1.70	215.57

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $2972.87/acre

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Table C.12: Nitrogen fertilizer price raised to 0.55/lb

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discountedNR $/acre
1	3.82	67.93	27.58	21.02	60.00	130.00	1.58	215.64
2	3.82	67.93	27.58	20.30	59.38	130.62	1.59	215.57
3	3.82	67.93	27.58	19.65	58.75	131.25	1.59	215.50
4	3.82	67.93	27.58	19.06	58.12	131.88	1.60	215.43
5	3.82	67.93	27.58	18.53	57.48	132.52	1.60	215.36
6	3.82	67.93	27.58	18.06	56.83	133.17	1.61	215.29
7	3.82	67.93	27.58	17.63	56.17	133.83	1.62	215.22
8	3.82	67.93	27.58	17.25	55.50	134.50	1.62	215.15
9	3.82	67.93	27.58	16.90	54.83	135.17	1.63	215.08
10	3.82	67.93	27.58	16.59	54.15	135.85	1.64	215.01
11	3.82	67.93	27.58	16.31	53.46	136.54	1.64	214.93
12	3.82	67.93	27.58	16.06	52.76	137.24	1.65	214.86
13	3.82	67.93	27.58	15.83	52.07	137.93	1.66	214.78
14	3.82	67.93	27.58	15.63	51.38	138.62	1.66	214.71
15	3.82	67.93	27.58	15.44	50.69	139.31	1.67	214.64
16	3.82	67.93	27.58	15.28	50.01	139.99	1.68	214.56
17	3.82	67.93	27.58	15.13	49.33	140.67	1.68	214.49
18	3.82	67.93	27.58	14.99	48.66	141.34	1.69	214.42
19	3.82	67.93	27.58	14.87	48.00	142.00	1.69	214.35
20	3.82	67.93	27.58	14.77	47.35	142.65	1.70	214.28

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $2955.09/acre

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Table C.13: Nitrogen fertilizer application limited to 67 lbs/acre

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discountedNR $/acre
1	3.84	67	24.97	21.02	60.00	130.00	1.59	211.39
2	3.84	67	24.97	20.17	59.38	130.62	1.59	211.33
3	3.84	67	24.97	19.40	58.75	131.25	1.60	211.26
4	3.84	67	24.97	18.71	58.11	131.89	1.61	211.19
5	3.84	67	24.97	18.08	57.47	132.53	1.61	211.12
6	3.84	67	24.97	17.52	56.81	133.19	1.62	211.05
7	3.84	67	24.97	17.02	56.15	133.85	1.62	210.98
8	3.84	67	24.97	16.57	55.48	134.52	1.63	210.91
9	3.84	67	24.97	16.16	54.81	135.19	1.64	210.83
10	3.84	67	24.97	15.79	54.13	135.87	1.64	210.76
11	3.84	67	24.97	15.46	53.43	136.57	1.65	210.69
12	3.84	67	24.97	15.16	52.73	137.27	1.66	210.61
13	3.84	67	24.97	14.89	52.04	137.96	1.66	210.54
14	3.84	67	24.97	14.65	51.34	138.66	1.67	210.46
15	3.84	67	24.97	14.44	50.65	139.35	1.68	210.38
16	3.84	67	24.97	14.24	49.96	140.04	1.68	210.31
17	3.84	67	24.97	14.07	49.28	140.72	1.69	210.24
18	3.84	67	24.97	13.91	48.61	141.39	1.70	210.16
19	3.84	67	24.97	13.77	47.95	142.06	1.70	210.09
20	3.84	67	24.97	13.64	47.29	142.71	1.71	210.02

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $2896.75/acre

LUBBOCK

Table C.14: Irrigation water use restricted to 0.50 acre inches less per acre from the average base value along with a restriction on fertilizer use

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discountedNR $/acre
1	3.32	67	24.96	21.02	60.00	130.00	1.37	146.11
2	3.32	67	24.96	20.17	59.46	130.54	1.38	146.06
3	3.32	67	24.96	19.40	58.92	131.08	1.38	146.01
4	3.32	67	24.96	18.71	58.37	131.63	1.39	145.96
5	3.32	67	24.96	18.08	57.81	132.19	1.39	145.91
6	3.32	67	24.96	17.52	57.24	132.76	1.40	145.86
7	3.32	67	24.96	17.02	56.67	133.33	1.40	145.80
8	3.32	67	24.96	16.57	56.10	133.90	1.40	145.75
9	3.32	67	24.96	16.16	55.51	134.49	1.41	145.69
10	3.32	67	24.96	15.79	54.92	135.08	1.41	145.64
11	3.32	67	24.96	15.46	54.32	135.68	1.42	145.58
12	3.32	67	24.96	15.16	53.72	136.28	1.42	145.53
13	3.32	67	24.96	14.89	53.12	136.88	1.43	145.47
14	3.32	67	24.96	14.65	52.52	137.48	1.43	145.41
15	3.32	67	24.96	14.44	51.92	138.08	1.44	145.36
16	3.32	67	24.96	14.24	51.32	138.68	1.44	145.30
17	3.32	67	24.96	14.06	50.73	139.27	1.45	145.25
18	3.32	67	24.96	13.91	50.15	139.85	1.45	145.19
19	3.32	67	24.96	13.76	49.58	140.42	1.46	145.14
20	3.32	67	24.96	13.64	49.01	140.99	1.46	145.09

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $2001.75/acre

LUBBOCK

Table C.15: Sale of water rights by around 1 acre inches per acre per year

years	irr	fert	percolation	nitconc	satthickness	plift	pcost	discounted NR
	ac-in/acre	lbs/acre	lbs/acre	mg/liter	feet	feet	$/ac-in	$/acre
1	2.82	67.93	27.57	21.02	60.00	130.00	1.17	224.20
2	2.82	67.93	27.57	20.30	59.54	130.46	1.17	224.09
3	2.82	67.93	27.57	19.65	59.08	130.92	1.17	223.99
4	2.82	67.93	27.57	19.06	58.61	131.39	1.18	223.89
5	2.82	67.93	27.58	18.53	58.14	131.86	1.18	223.79
6	2.82	67.93	27.58	18.06	57.66	132.34	1.18	223.70
7	2.82	67.93	27.58	17.63	57.17	132.83	1.19	223.66
8	2.82	67.93	27.58	17.25	56.68	133.32	1.19	223.62
9	2.82	67.93	27.58	16.90	56.19	133.82	1.19	223.58
10	2.82	67.93	27.58	16.59	55.68	134.32	1.20	223.54
11	2.82	67.93	27.58	16.31	55.17	134.83	1.20	223.50
12	2.82	67.93	27.58	16.06	54.66	135.34	1.20	223.46
13	2.82	67.93	27.58	15.83	54.15	135.85	1.21	223.42
14	2.82	67.93	27.58	15.63	53.64	136.36	1.21	223.38
15	2.82	67.93	27.58	15.44	53.13	136.87	1.22	223.34
16	2.82	67.93	27.58	15.28	52.62	137.38	1.22	223.30
17	2.82	67.93	27.58	15.13	52.12	137.88	1.22	223.26
18	2.82	67.93	27.58	14.99	51.63	138.37	1.23	223.22
19	2.82	67.93	27.58	14.87	51.14	138.86	1.23	223.12
20	2.82	67.93	27.58	14.77	50.66	139.34	1.23	223.04

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $3072.11/acre

LUBBOCK

Table C.16: Sale of water rights by around 1 acre inches per acre per year with fertilizer use restriction

years	irr	fert	percolation	nitconc	satthickness	plift	pcost	discounted NR
	ac-in/acre	lbs/acre	lbs/acre	mg/liter	feet	feet	$/ac-in	$/acre
1	2.84	67	24.97	21.02	60.00	130.00	1.17	216.72
2	2.84	67	24.97	20.17	59.54	130.46	1.18	216.62
3	2.84	67	24.97	19.40	59.07	130.93	1.18	216.51
4	2.84	67	24.97	18.71	58.60	131.40	1.18	216.41
5	2.84	67	24.97	18.08	58.13	131.87	1.19	216.31
6	2.84	67	24.97	17.52	57.64	132.36	1.19	216.22
7	2.84	67	24.97	17.02	57.15	132.85	1.19	216.18
8	2.84	67	24.97	16.57	56.66	133.34	1.20	216.14
9	2.84	67	24.97	16.16	56.16	133.84	1.20	216.10
10	2.84	67	24.97	15.79	55.66	134.35	1.21	216.06
11	2.84	67	24.97	15.46	55.14	134.86	1.21	216.02
12	2.84	67	24.97	15.16	54.62	135.38	1.21	215.98
13	2.84	67	24.97	14.90	54.11	135.89	1.22	215.94
14	2.84	67	24.97	14.65	53.60	136.40	1.22	215.90
15	2.84	67	24.97	14.44	53.09	136.91	1.22	215.85
16	2.84	67	24.97	14.24	52.58	137.43	1.23	215.81
17	2.84	67	24.97	14.07	52.07	137.93	1.23	215.77
18	2.84	67	24.97	13.91	51.58	138.43	1.23	215.73
19	2.84	67	24.97	13.77	51.08	138.92	1.24	215.64
20	2.84	67	24.97	13.64	50.60	139.40	1.24	215.55

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $2969.95/acre

LUBBOCK

Table C.17: Discounted net revenues under the different policies

years	base $/acre	nitp_0.53 $/acre	nitp_0.55 $/acre	constraint $/acre	quota $/acre	buyout $/acre
1	218.87	216.93	215.64	211.39	146.11	224.20
2	218.80	216.86	215.57	211.33	146.06	224.09
3	218.74	216.80	215.50	211.26	146.01	223.99
4	218.67	216.73	215.43	211.19	145.96	223.89
5	218.60	216.66	215.36	211.12	145.91	223.79
6	218.53	216.59	215.29	211.05	145.86	223.70
7	218.46	216.52	215.22	210.98	145.80	223.66
8	218.39	216.45	215.15	210.91	145.75	223.62
9	218.31	216.37	215.08	210.83	145.69	223.58
10	218.24	216.30	215.01	210.76	145.64	223.54
11	218.17	216.23	214.93	210.69	145.58	223.50
12	218.09	216.15	214.86	210.61	145.53	223.46
13	218.02	216.08	214.78	210.54	145.47	223.42
14	217.94	216.00	214.71	210.46	145.41	223.38
15	217.87	215.93	214.64	210.38	145.36	223.34
16	217.80	215.86	214.56	210.31	145.30	223.30
17	217.72	215.78	214.49	210.24	145.25	223.26
18	217.65	215.71	214.42	210.16	145.19	223.22
19	217.58	215.64	214.35	210.09	145.14	223.12
20	217.51	215.57	214.28	210.02	145.09	223.04

Note::*nitp_0.53* and *nitp_0.55* refer to price of fertilizer being raised by 5% and 10% respectively.*Constraint* refers to the restriction on fertilizer use by 144 lbs per acre, *quota* denotes the restriction of irrigation water use by $0.50 per acre inch from the average base value. *satt_50* refers to the saturated thickness being restricted to 50 feet at the end of the terminal period, while *buyout* denotes the purchase of water rights by around 2 acre inches per acre by the Groundwater Conservation District.

Table C.18: Nitrate concentration levels under the different policies

years	base mg/liter	nitp_0.52 mg/liter	nitp_0.55 mg/liter	constraint mg/liter	quota mg/liter	buyout mg/liter
1	21.02	21.02	21.02	21.02	21.02	21.02
2	20.30	20.30	20.30	20.17	20.17	20.30
3	19.65	19.65	19.65	19.40	19.40	19.65
4	19.06	19.06	19.06	18.71	18.71	19.06
5	18.53	18.53	18.53	18.08	18.08	18.53
6	18.06	18.06	18.06	17.52	17.52	18.06
7	17.63	17.63	17.63	17.02	17.02	17.63
8	17.25	17.25	17.25	16.57	16.57	17.25
9	16.90	16.90	16.90	16.16	16.16	16.90
10	16.59	16.59	16.59	15.79	15.79	16.59
11	16.31	16.31	16.31	15.46	15.46	16.31
12	16.06	16.06	16.06	15.16	15.16	16.06
13	15.83	15.83	15.83	14.89	14.89	15.83
14	15.63	15.63	15.63	14.65	14.65	15.63
15	15.44	15.44	15.44	14.44	14.44	15.44
16	15.28	15.28	15.28	14.24	14.24	15.28
17	15.13	15.13	15.13	14.07	14.06	15.13
18	14.99	14.99	14.99	13.91	13.91	14.99
19	14.87	14.87	14.87	13.77	13.76	14.87
20	14.77	14.77	14.77	13.64	13.64	14.77

Note::*nitp_0.53* and *nitp_0.55* refer to price of fertilizer being raised by 5% and 10% respectively.*Constraint* refers to the restriction on fertilizer use by 144 lbs per acre, *quota* denotes the restriction of irrigation water use by $0.50 per acre inch from the average base value. *satt_50* refers to the saturated thickness being restricted to 50 feet at the end of the terminal period, while *buyout* denotes the purchase of water rights by around 2 acre inches per acre by the Groundwater Conservation District.

APPENDIX D

Groundwater definitions

(1) **Porosity**: If a volume of saturated aquifer material is completely dried, the water volume removed reflects the total*porosity* of the material, or the fraction of pore space within the total volume of solids plus open spaces.

(2) **Specific yield**:A characteristic closely related to effective porosity is the *specific yield*of the aquifer, which is the volume of water per unit volume of aquifer that can be extracted by pumping. Although there are some technical distinctions, effective porosity and specific yield can be thought of as equivalent for most non-technical purposes.

Specific yield (SY) is clearly an important factor in water availability, and is the factor that is used to convert saturated thickness (ST) to the actual volume of groundwater available;

Volume = Area x ST x SY

(3) **Storativity**: It is a measure of the impact on groundwater levels in the aquifer of extracting one unit of water. It is a dimensionless parameter, defined for a confined aquifer as the volume of water released from storage per unit of surface area per unit decrease in the hydraulic head.

(4) **Transmissivity**: It is a measure of the speed and extent to which the impacts of any changes in the aquifer pass through it. Aquifer t is defined as the hydraulic conductivity of an aquifer multiplied by its thickness, where hydraulic conductivity is a constant of proportionality relating specific discharge from a region to the hydraulic gradient across it.

(5) **Vadose zone:** Region of aeration above the water table. This zone also includes the capillary fringe above the water table, the height of which will vary according to the grain size of the sediments. In coarse-grained mediums the fringe may be flat at the top and thin, whereas in finer grained material it will tend to be higher and may be very irregular along the upper surface. The vadose zone varies widely in thickness, from being absent to many hundreds of feet, depending upon several factors. These include the environment and the type of earth material present.

(6) **Saturated thickness**: Vertical thickness of the hydro geologically defined aquifer in which the pore spaces are filled (saturated) with water. Basically, it represents the total depth of water in the aquifer.

(7) **Pumping lift**: The pumping lift of an aquifer is defined as the depth to the water table. It refers to the vertical distance between the surface of the aquifer and the water table below.

(8) **Nitrogen percolation**: The deep underground movement of the nitrogen fertilizer applied. It is termed as nitrogen percolation or nitrogen leaching below the vadose zone.

APPENDIX E

Base Run for Lynn County

years	**irr** ac-in/acre	**fert** lbs/acre	**percolation** lbs/acre	**nitconc** mg/liter	**satthickness** feet	**plift** feet	**pcost** $/ac-in	**discounted NR** $/acre
1	4.63	74.04	49.98	45.95	43.00	62.00	1.14	208.24
2	4.63	74.04	49.98	44.35	42.63	62.37	1.14	208.20
3	4.63	74.04	49.98	42.92	42.26	62.74	1.15	208.15
4	4.63	74.04	49.98	41.62	41.88	63.12	1.15	208.10
5	4.63	74.04	49.98	40.46	41.50	63.50	1.16	208.05
6	4.63	74.04	49.98	39.41	41.11	63.89	1.16	208.00
7	4.63	74.04	49.98	38.47	40.72	64.28	1.17	207.95
8	4.63	74.04	49.98	37.62	40.33	64.67	1.17	207.90
9	4.63	74.04	49.98	36.86	39.93	65.07	1.17	207.84
10	4.63	74.04	49.98	36.17	39.53	65.47	1.18	207.79
11	4.63	74.04	49.98	35.55	39.12	65.88	1.18	207.74
12	4.63	74.04	49.98	35.00	38.72	66.29	1.19	207.69
13	4.63	74.04	49.98	34.50	38.30	66.70	1.19	207.63
14	4.63	74.04	49.98	34.04	37.88	67.12	1.20	207.58
15	4.63	74.04	49.98	33.64	37.46	67.54	1.20	207.52
16	4.63	74.04	49.98	33.27	37.04	67.96	1.21	207.47
17	4.63	74.04	49.98	32.94	36.61	68.39	1.21	207.41
18	4.63	74.04	49.98	32.65	36.18	68.83	1.22	207.36
19	4.63	74.04	49.98	32.38	35.74	69.26	1.22	207.30
20	4.63	74.04	49.98	32.14	35.30	69.70	1.23	207.24

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $2,855.66 /acre

Base Run for Terry County

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discounted NR $/acre
1	4.71	80.37	59.66	31.25	47.00	94.00	1.53	200.74
2	4.71	80.37	59.66	31.11	46.40	94.60	1.54	200.66
3	4.71	80.37	59.66	30.98	45.80	95.20	1.55	200.58
4	4.71	80.37	59.66	30.87	45.19	95.81	1.55	200.50
5	4.71	80.37	59.66	30.76	44.59	96.41	1.56	200.42
6	4.71	80.37	59.66	30.67	43.97	97.03	1.57	200.34
7	4.71	80.37	59.66	30.59	43.34	97.66	1.57	200.26
8	4.71	80.37	59.66	30.51	42.71	98.29	1.58	200.17
9	4.71	80.37	59.66	30.44	42.06	98.94	1.59	200.09
10	4.71	80.37	59.66	30.38	41.41	99.59	1.60	200.00
11	4.71	80.37	59.66	30.33	40.74	100.26	1.60	199.91
12	4.71	80.37	59.66	30.28	40.07	100.93	1.61	199.82
13	4.71	80.37	59.66	30.23	39.40	101.60	1.62	199.74
14	4.71	80.37	59.66	30.19	38.73	102.27	1.63	199.65
15	4.71	80.37	59.66	30.16	38.05	102.95	1.64	199.56
16	4.71	80.37	59.66	30.12	37.37	103.63	1.64	199.47
17	4.71	80.37	59.66	30.09	36.69	104.31	1.65	199.38
18	4.71	80.37	59.66	30.07	36.03	104.98	1.66	199.29
19	4.71	80.37	59.66	30.04	35.36	105.64	1.67	199.20
20	4.71	80.37	59.66	30.02	34.70	106.30	1.67	199.11

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $2,749.04/ acre

Base Run for BaileyCounty

years	irr	fert	percolation	nitconc	satthickness	plift	pcost	discounted NR
	ac-in/acre	lbs/acre	lbs/acre	mg/liter	feet	feet	$/ac-in	$/acre
1	8.87	109.21	60.88	13.81	62.00	111.00	3.25	434.74
2	8.87	109.21	60.88	14.86	61.30	111.70	3.27	434.56
3	8.87	109.21	60.88	15.81	60.61	112.39	3.28	434.39
4	8.87	109.21	60.88	16.67	59.95	113.06	3.30	434.23
5	8.87	109.21	60.88	17.44	59.29	113.71	3.31	434.06
6	8.87	109.21	60.88	18.13	58.65	114.35	3.33	433.90
7	8.87	109.21	60.88	18.75	58.01	114.99	3.34	433.74
8	8.87	109.21	60.88	19.31	57.39	115.61	3.35	433.59
9	8.87	109.21	60.88	19.81	56.78	116.22	3.37	433.44
10	8.87	109.21	60.88	20.27	56.15	116.85	3.38	433.28
11	8.87	109.21	60.88	20.68	55.54	117.47	3.39	433.13
12	8.87	109.21	60.88	21.04	54.91	118.09	3.41	432.97
13	8.87	109.21	60.88	21.38	54.29	118.71	3.42	432.82
14	8.87	109.21	60.88	21.67	53.68	119.32	3.43	432.66
15	8.87	109.21	60.88	21.94	53.09	119.91	3.45	432.52
16	8.87	109.21	60.88	22.18	52.51	120.50	3.46	432.37
17	8.87	109.21	60.88	22.40	51.95	121.06	3.47	432.23
18	8.87	109.21	60.88	22.59	51.41	121.59	3.48	432.10
19	8.87	109.21	60.88	22.77	50.90	122.10	3.50	431.97
20	8.87	109.21	60.88	22.93	50.41	122.59	3.51	431.85

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: 5955.726/acre

Base Run for Lamb County

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discounted NR $/acre
1	6.46	100.24	43.26	14.23	64.00	167.00	3.26	409.99
2	6.46	100.24	43.26	14.54	62.82	168.19	3.28	409.77
3	6.46	100.24	43.26	14.81	61.63	169.37	3.30	409.56
4	6.46	100.24	43.26	15.06	60.45	170.55	3.31	409.34
5	6.46	100.24	43.26	15.29	59.26	171.74	3.33	409.12
6	6.46	100.24	43.26	15.49	58.05	172.95	3.35	408.91
7	6.46	100.24	43.26	15.67	56.84	174.16	3.37	408.69
8	6.46	100.24	43.26	15.83	55.63	175.38	3.39	408.47
9	6.46	100.24	43.26	15.98	54.40	176.60	3.41	408.24
10	6.46	100.24	43.26	16.11	53.17	177.83	3.43	408.02
11	6.46	100.24	43.26	16.23	51.93	179.07	3.45	407.80
12	6.46	100.24	43.26	16.34	50.68	180.32	3.47	407.57
13	6.46	100.24	43.26	16.43	49.45	181.56	3.49	407.34
14	6.46	100.24	43.26	16.52	48.21	182.79	3.51	407.12
15	6.46	100.24	43.26	16.60	46.98	184.02	3.53	406.90
16	6.46	100.24	43.26	16.67	45.75	185.25	3.55	406.67
17	6.46	100.24	43.26	16.73	44.53	186.47	3.57	406.45
18	6.46	100.24	43.26	16.79	43.33	187.67	3.59	406.23
19	6.46	100.24	43.26	16.84	42.13	188.87	3.60	406.02
20	6.46	100.24	43.26	16.89	40.95	190.05	3.62	405.80

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: 6566.585/acre

Base Run for Parmer County

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discounted NR $/acre
1	7.70	159.71	104.37	9.43	73.00	305.00	6.50	465.22
2	7.70	159.75	104.47	10.57	71.55	306.45	6.53	464.90
3	7.70	159.79	104.58	11.61	70.11	307.89	6.55	464.59
4	7.70	159.84	104.71	12.54	68.67	309.33	6.58	464.28
5	7.69	159.89	104.85	13.38	67.22	310.78	6.60	463.96
6	7.69	159.94	104.98	14.14	65.73	312.27	6.63	463.64
7	7.69	159.99	105.12	14.82	64.22	313.78	6.66	463.31
8	7.69	160.03	105.23	15.44	62.69	315.32	6.69	462.98
9	7.69	160.07	105.34	16.00	61.13	316.87	6.71	462.64
10	7.69	160.11	105.44	16.51	59.55	318.45	6.74	462.30
11	7.69	160.12	105.48	16.97	57.96	320.04	6.77	461.96
12	7.69	160.16	105.59	17.38	56.41	321.59	6.80	461.62
13	7.68	160.19	105.65	17.75	54.82	323.18	6.83	461.28
14	7.68	160.21	105.71	18.09	53.24	324.77	6.86	460.94
15	7.68	160.21	105.73	18.40	51.65	326.35	6.89	460.59
16	7.68	160.23	105.76	18.67	50.13	327.87	6.92	460.27
17	7.68	160.24	105.80	18.92	48.63	329.37	6.94	459.94
18	7.68	160.25	105.83	19.14	47.11	330.89	6.97	459.61
19	7.68	160.26	105.84	19.35	45.60	332.40	7.00	459.29
20	7.68	160.26	105.85	19.53	44.10	333.90	7.03	458.96

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $6356.553/acre

Base Run for Hockley County

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/ac-in	discounted NR $/acre
1	3.80	68.85	25.92	13.57	39.00	133.00	1.60	199.13
2	3.80	68.85	25.92	13.25	38.49	133.51	1.60	199.08
3	3.80	68.85	25.92	12.96	37.97	134.03	1.61	199.02
4	3.80	68.85	25.92	12.70	37.45	134.55	1.61	198.97
5	3.80	68.85	25.92	12.47	36.93	135.07	1.62	198.91
6	3.80	68.85	25.92	12.26	36.40	135.60	1.62	198.85
7	3.80	68.85	25.92	12.07	35.86	136.14	1.63	198.80
8	3.80	68.85	25.92	11.90	35.32	136.68	1.63	198.74
9	3.80	68.85	25.92	11.75	34.76	137.24	1.64	198.68
10	3.80	68.85	25.92	11.61	34.20	137.80	1.64	198.62
11	3.80	68.85	25.92	11.48	33.62	138.38	1.65	198.56
12	3.80	68.85	25.92	11.37	33.03	138.97	1.65	198.49
13	3.80	68.85	25.92	11.27	32.45	139.56	1.66	198.43
14	3.80	68.85	25.92	11.18	31.85	140.15	1.67	198.37
15	3.80	68.85	25.92	11.10	31.25	140.75	1.67	198.30
16	3.80	68.85	25.92	11.03	30.65	141.35	1.68	198.24
17	3.80	68.85	25.92	10.96	30.06	141.94	1.68	198.18
18	3.80	68.85	25.92	10.90	29.48	142.52	1.69	198.11
19	3.80	68.85	25.92	10.85	28.91	143.09	1.69	198.05
20	3.80	68.85	25.92	10.80	28.34	143.67	1.70	197.99

Note: *Irr* represents the amount of irrigation water applied per acre, *fert* represents the amount of nitrogen fertilizer applied per acre, *percolation* denotes the amount of fertilizer that percolates below the root zone, *nitconc* denotes the level of nitrate in the water, *satthickness* represents the saturated thickness of the aquifer, *plift* is the pumping lift of the aquifer, *pcost* is the pumping cost per acre inch and *discounted NR* represents the discounted value of net revenues over the years from this activity.

NPV: $2729.67/acre

APPENDIX F

GAMS MODEL FOR THE BASE SOLUTION

```
$TITLE  BASE MODEL FOR CASTRO COUNTY
$OFFUPPER OFFSYMXREF OFFSYMLIST OFFUELLIST OFFUELXREF
OPTION LIMROW=0, LIMCOL=0
OPTION NLP=CONOPT
*OPTION NLP=MINOS
SETS
t time period /1*20/
k crops /corn,sorghum,cotton,wheat/
tfirst(t)  first period
tlast(t)  last period;
tfirst(t) = yes$(ord(t)eq 1);
tlast(t) = yes$(ord(t) eq card(t));
SCALARS
EF energy use factor for electricity /0.164/
EP energy price /0.09/
EFF pump engine efficiency /0.50/
PSI system operating pressure /16.5/
S  specific yield of the aquifer /0.15/
A land area overlaying Ogallala /574720/
ILIFT initial pumping lift of the aquifer/233/
RECH  recharge rate /0.0001/
IS initial sat thickness of aquifer /79/
ICONC /6.37/
Pmo price of nit fertilizer /0.50/
eta scaling factor /0.02/
del decay rate/0.10/
r  discount rate /0.05/
```

```
PARAMETERCP(k) crop prices
*corn $/bu,cotton $/lb sorghum$/bu wheat $/bu
/corn 3.89, cotton 0.56, sorghum 3.47, wheat 5.69/
PARAMETERHC(k) harvest and hauling costs
*corn $/bu, cotton $/lb, sorghum $/bu, wheat $/bu
/corn 0.40, cotton 0.40,sorghum 0.34, wheat 0.50/
PARAMETERLH(k) labor hours allotted per acre
/corn 1.28,cotton 0.77,sorghum 0.89, wheat 0.96/
PARAMETERLC(k) labor costs of irrigation per hour
/corn 10,cotton 10,sorghum 10, wheat 10 /
PARAMETERMC(k) repair and maintenance costs per acre
/corn 2.00,cotton 2.00, sorghum 2.00, wheat 2.00/
PARAMETERFC(k) fixed expenses
/corn 40,cotton 40, sorghum 40, wheat 40/
PARAMETEROP(k)
/corn 13.52,cotton 14.98, sorghum 8.91, wheat 12.88/
PARAMETERirrla(k) irrigated land acreage for crops
/corn 101660,cotton 66380, sorghum 20700, wheat 84060/;

SCALARS
*Puts lower bounds
Minirrcor minimum irrigation water requirements for corn /4/
Minirrcot minimum irrigation water requirements for cotton /3/
Minirrs minimum irrigation water requirements for sorghum /4/
Minirrw minimum irrigation water requirements for wheat
/4/;
*GPC gross pumping capacity /500/
*1 acre inch=27154.28gallons
SCALAR disc discount;
disc=1/(1+r);
PARAMETER delta discount factor;
delta(t)=(disc**(ord(t)-1))
PARAMETERirrlabc; irrigation labor cost
irrlabc=sum(k,LH(k)*LC(k))
PARAMETERfcost; fixed expenses
```

```
fcost=sum(k,FC(k))
PARAMETERopcap; operating capital expenses
opcap=sum(k,OP(k))
PARAMETERtotirrac; total land area irrigated
totirrac= sum(k,irrla(k));

*actual trend forecast
SCALARia irrigated acres over time
ia1   /242171.42/
ia2   /240961.51/
ia3    /239751.59/
ia4    /238541.68/
ia5    /237331.76/
ia6    /236121.84/
ia7    /234911.92/
ia8   /233702.01/
ia9    /232492.09/
ia10   /231282.18/
ia11   /227652.42/
ia12   /228862.34/
ia13   /225232.58/
ia14   /224022.66/
ia15   /222812.75/
ia16   /221602.83/
ia17   /222812.76/
ia18   /221602.84/
ia19   /220392.92/
ia20  /219183.00/;

VARIABLES x
gyld(k,t) grain yield per acre for crop k
irr(k,t) irrigation water applied per acre for crop k
fert(k,t) fertilizer applied per acre for crop k
irrtot(t) net irrigation water applied per acre
ferttot(t) net fertilizer applied per acre
```

```
perc(k,t)percolation of nutrient for crop k
nperc(t) weighted average of percolation of nitrogen fertilizer
soiln(k,t) soil nitrogen available per acre for crop k
prk(k,t) percolation below root zone for crop k
prec(t) precipitation level
conc(t) nitrate concentration
hvstc(t) per acre harvest and hauling cost
mcost(t)per acre maintenance cost
nopumpcost(t) total cost without pumping costs
pcost(t)pumping cost per acre inch
cost(t) total costs incurred
satt(t) saturated thickness of aquifer in the county
plift(t) pumping lift of the aquifer
GPC(t) gross pumping capacity of the aquifer
NR(t) net revenue per acre
NPVC net present value of production/ benefits per acre

POSITIVE VARIABLES x
perc(k,t)
nperc(t)

EQUATIONS
yieldcor(t) yield equation for corn per acre
yieldc(t)yield equation for cotton per acre
yields(t)yield equation for sorghum per acre
yieldw(t)yield equation for wheat per acre
waterdd(t)  water use equation per acre
fertappl(t) fertilizer use equation per acre
nperccor(t) percolation equation for corn
npercs(t) percolation equation for sorghum
npercw(t) percolation equation for wheat
npercc(t) percolation equation for cotton
totperc(t) total percolation equation
*cost equations
thvstc(t) total harvest and hauling cost equation
```

```
tmc(t)total maintenance cost equation
tnopumpc(t)  total nonpumping cost equation
tcost(t) total cost equation
plimit(t) pumping limit equation
pcapacity(t) pumping capacity equation
*Minimum input use equations
mirrcor(t)
mirrs(t)
mirrc(t)
mirrw(t)
mfertcor(t)
mferts(t)
mfertc(t)
mfertw(t)
*appllim(t)
netrev(t) net returns from production
obj  maximizing discounted net returns

*pumping lift transition equations
lift1
lift2
lift3
lift4
lift5
lift6
lift7
lift8
lift9
lift10
lift11
lift12
lift13
lift14
lift15
lift16
```

```
lift17
lift18
lift19
*Pumping cost equation
pumpc(t)
transition equations for saturated thickness
sat1
sat2
sat3
sat4
sat5
sat6
sat7
sat8
sat9
sat10
sat11
sat12
sat13
sat14
sat15
sat16
sat17
sat18
sat19
nconc(t) nitrate conc transition equation
water stock balance equations
stockb1
stockb2
stockb3
stockb4
stockb5
stockb6
stockb7
stockb8
```

```
stockb9
stockb10
stockb11
stockb12
stockb13
stockb14
stockb15
stockb16
stockb17
stockb18
stockb19
stockb20
waterdd(t); net water demand equations

*CROP YIELD EQUATIONS
yieldcor(t)..gyld("corn",t)=E= -
120.783+15.991*irr("corn",t)+0.4767*fert("corn",t)-
0.37981*irr("corn",t)**2-
0.0000578*fert("corn",t)**2+0.02163*(irr("corn",t)*fert("corn",t)
)**2;
yieldc(t)..gyld("cotton",t)=E=530.68+0.79*(irr("cotton",t)*fert("
cotton",t))-0.0002*(irr("cotton",t)*fert("cotton",t))**2;
yields(t)..gyld("sorghum",t)=E=28.94+0.044*(irr("sorghum",t)*fert
("sorghum",t))-0.0000064*(irr("sorghum",t)*fert("sorghum",t))**2;
yieldw(t)..gyld("wheat",t)=E=13.22+0.006*(irr("wheat",t)*fert("wh
eat",t))-0.00000252*(irr("wheat",t)*fert("wheat",t))**2;
*COST EQUATIONS
thvstc(t)..hvstc(t)=E=sum(k,hvstc(t)*gyld(k,t));
tmc(t)..mcost(t)=E=sum(k,MC(k)*irr(k,t));
tnopumpc(t)..nopumpcost(t)=E=(irrlabc+hvstc(t)+fcost+mcost(t)+opc
ap);
tcost(t).. cost(t)=E=pcost(t)+Pmo*ferttot(t)+nopumpcost(t);

*INPUT DEMAND EQUATIONS
waterdd(t)..irrtot(t)=E=sum(k,irr(k,t)*irrla(k))/totirrac;
fertappl(t)..ferttot(t)=E=sum(k,fert(k,t)*irrla(k))/totirrac;

mirrcor(t)..irr("corn",t)=G=minirrcor;
```

```
mirrs(t)..irr("sorghum",t)=G=minirrs;
mirrc(t)..irr("cotton",t)=G=minirrcot;
mirrw(t)..irr("wheat",t)=G=minirrw;

mfertcor(t)..fert("corn",t)=G=119.98;
mferts(t)..fert("sorghum",t)=G=85.7;
mfertc(t)..fert("cotton",t)=G=49.63;
mfertw(t)..fert("wheat",t)=G=108.27;
*NET REVENUE CALCULATION
netrev(t)..NR(t)=E=sum(k,CP(k)*gyld(k,t)*irrla(k))-cost(t);
pcapacity(t)..GPC(t)=E=28.25*((satt(t)*12)/210)**2;
*Pumping restriction
plimit(t)..irrtot(t)=L=GPC(t);
obj..NPVB=E=sum(t,NR(t)*delta(t));
lift1..plift("2")=E=plift("1")+((irrtot("1")-RECH)*ia1/12)/(A*S);
lift2..plift("3")=E=plift("2")+((irrtot("2")-RECH)*ia2/12)/(A*S);
lift3..plift("4")=E=plift("3")+((irrtot("3")-RECH)*ia3/12)/(A*S);
lift4..plift("5")=E=plift("4")+((irrtot("4")-RECH)*ia4/12)/(A*S);
lift5..plift("6")=E=plift("5")+((irrtot("5")-RECH)*ia5/12)/(A*S);
lift6..plift("7")=E=plift("6")+((irrtot("6")-RECH)*ia6/12)/(A*S);
lift7..plift("8")=E=plift("7")+((irrtot("7")-RECH)*ia7/12)/(A*S);
lift8..plift("9")=E=plift("8")+((irrtot("8")-RECH)*ia8/12)/(A*S);
lift9..plift("10")=E=plift("9")+((irrtot("9")-
RECH)*ia9/12)/(A*S);
lift10..plift("11")=E=plift("10")+((irrtot("10")-
RECH)*ia10/12)/(A*S);
lift11..plift("12")=E=plift("11")+((irrtot("11")-
RECH)*ia11/12)/(A*S);
lift12..plift("13")=E=plift("12")+((irrtot("12")-
RECH)*ia12/12)/(A*S);
lift13..plift("14")=E=plift("13")+((irrtot("13")-
RECH)*ia13/12)/(A*S);
lift14..plift("15")=E=plift("14")+((irrtot("14")-
RECH)*ia14/12)/(A*S);
lift15..plift("16")=E=plift("15")+((irrtot("15")-
RECH)*ia15/12)/(A*S);
lift16..plift("17")=E=plift("16")+((irrtot("16")-
RECH)*ia16/12)/(A*S);
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lift17..plift("18")=E=plift("17")+((irrtot("17")-
RECH)*ia17/12)/(A*S);
lift18..plift("19")=E=plift("18")+((irrtot("18")-
RECH)*ia18/12)/(A*S);
lift19..plift("20")=E=plift("19")+((irrtot("19")-
RECH)*ia19/12)/(A*S);


*NITROGEN PERCOLATION EQUATIONS
nperccor(t)..perc("corn",t)=E=-
0.32+0.20*prk("corn",t)+0.009*prec(t)-0.007*gyld("corn",t)-
0.004*soiln("corn",t)-0.029*irr("corn",t)+0.011*fert("corn",t);
npercc(t)..perc("cotton",t)=E=1.91+31.18*prk("cotton",t)-
5.77*prec(t)-0.12*gyld("cotton",t)-0.06*soiln("cotton",t)-
17.28*irr("cotton",t)+2.09*fert("cotton",t);
npercs(t)..perc("sorghum",t)=E=-
11.09+0.228*prk("sorghum",t)+1.031*prec(t)-
0.264*gyld("sorghum",t)-
0.897*soiln("sorghum",t)+0.235*irr("sorghum",t)+0.705*fert("sorgh
um",t);
npercw(t)..perc("wheat",t)=E=47.47+1.76*prk("wheat",t)-
4.918*prec(t)-2.269*gyld("wheat",t)-0.218*soiln("wheat",t)-
13.62*irr("wheat",t)+1.296*fert("wheat",t);
totperc(t)..nperc(t)=E=sum(k,perc(k,t)*irrla(k))/totirrac;
*Nitrate concentration equation of motion
nconc(t)..conc(t+1)=E=(1-del)*conc(t)+eta*nperc(t);


*EQUATIONS FOR PUMPING COST
pumpc(t)..pcost(t)=E=((EF*(plift(t)+2.31*PSI)*EP)/EFF)*irrtot(t);


*Checked with TWDB methodology
stockb1..irrtot("1")=L=(satt("1")*S*ia1)*12;
stockb2..irrtot("2")=L=(satt("2")*S*ia2)*12;
stockb3..irrtot("3")=L=(satt("3")*S*ia3)*12;
stockb4..irrtot("4")=L=(satt("4")*S*ia4)*12;
stockb5..irrtot("5")=L=(satt("5")*S*ia5)*12;
stockb6..irrtot("6")=L=(satt("6")*S*ia6)*12;
stockb7..irrtot("7")=L=(satt("7")*S*ia7)*12;
stockb8..irrtot("8")=L=(satt("8")*S*ia8)*12;
stockb9..irrtot("9")=L=(satt("9")*S*ia9)*12;
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stockb10..irrtot("10")=L=(satt("10")*S*ia10)*12;
stockb11..irrtot("11")=L=(satt("11")*S*ia11)*12;
stockb12..irrtot("12")=L=(satt("12")*S*ia12)*12;
stockb13..irrtot("13")=L=(satt("13")*S*ia13)*12;
stockb14..irrtot("14")=L=(satt("14")*S*ia14)*12;
stockb15..irrtot("15")=L=(satt("15")*S*ia15)*12;
stockb16..irrtot("16")=L=(satt("16")*S*ia16)*12;
stockb17..irrtot("17")=L=(satt("17")*S*ia17)*12;
stockb18..irrtot("18")=L=(satt("18")*S*ia18)*12;
stockb19..irrtot("19")=L=(satt("19")*S*ia19)*12;
stockb20..irrtot("20")=L=(satt("20")*S*ia19)*12;

*EQUATIONS FOR SATURATED THICKNESS
sat1..satt("2")=E=satt("1")-((irrtot("1")-RECH)*ia1/12)/(S*A);
sat2..satt("3")=E=satt("2")-((irrtot("2")-RECH)*ia2/12)/(S*A);
sat3..satt("4")=E=satt("3")-((irrtot("3")-RECH)*ia3/12)/(S*A);
sat4..satt("5")=E=satt("4")-((irrtot("4")-RECH)*ia4/12)/(S*A);
sat5..satt("6")=E=satt("5")-((irrtot("5")-RECH)*ia5/12)/(S*A);
sat6..satt("7")=E=satt("6")-((irrtot("6")-RECH)*ia6/12)/(S*A);
sat7..satt("8")=E=satt("7")-((irrtot("7")-RECH)*ia7/12)/(S*A);
sat8..satt("9")=E=satt("8")-((irrtot("8")-RECH)*ia8/12)/(S*A);
sat9..satt("10")=E=satt("9")-((irrtot("9")-RECH)*ia9/12)/(S*A);
sat10..satt("11")=E=satt("10")-((irrtot("10")-
RECH)*ia10/12)/(S*A);
sat11..satt("12")=E=satt("11")-((irrtot("11")-
RECH)*ia11/12)/(S*A);
sat12..satt("13")=E=satt("12")-((irrtot("12")-
RECH)*ia12/12)/(S*A);
sat13..satt("14")=E=satt("13")-((irrtot("13")-
RECH)*ia13/12)/(S*A);
sat14..satt("15")=E=satt("14")-((irrtot("14")-
RECH)*ia14/12)/(S*A);
sat15..satt("16")=E=satt("15")-((irrtot("15")-
RECH)*ia15/12)/(S*A);
sat16..satt("17")=E=satt("16")-((irrtot("16")-
RECH)*ia16/12)/(S*A);
sat17..satt("18")=E=satt("17")-((irrtot("17")-
RECH)*ia17/12)/(S*A);
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sat18..satt("19")=E=satt("18")-((irrtot("18")-
RECH)*ia18/12)/(S*A);
sat19..satt("20")=E=satt("19")-((irrtot("19")-
RECH)*ia19/12)/(S*A);

*INITIALIZATION OF STATE VARIABLES
plift.lo(t)=ILIFT;
plift.fx(tfirst(t))=plift.lo(t);
conc.lo(t)=0.01;
conc.fx(tfirst(t))=ICONC;
satt.fx(tfirst(t))=IS;

Average values simulated
prk.fx("corn",t)=0.863;
prec.fx(t)=13.14;
soiln.fx("corn",t)=64.08;
prk.fx("cotton",t)=1.12;
soiln.fx("cotton",t)=49.12;
prk.fx("sorghum",t)=57.43;
soiln.fx("sorghum",t)=3.467;
prk.fx("wheat",t)=61.92;
soiln.fx("wheat",t)=69.78;

*BOUNDS
fert.up("sorghum",t)=115.81;
fert.up("corn",t)=155.38;
irr.up("sorghum",t)=10;
irr.up("corn",t)=12;
modelnitleaching/all/;

PARAMETERREPORT(*,*);
Solve nitleaching maximizing NPVB using nlp;
report("Cornyld",t)=gyld.l("corn",t);
report("Soryld",t)=gyld.l("sorghum",t);
report("Cottyld",t)=gyld.l("cotton",t);
report("wheatyld",t)=gyld.l("wheat",t);
```

```
report("totfert",t)=ferttot.l(t);
report("totirr",t)=irrtot.l(t);
report("nitconc",t)=conc.l(t);
report("satthickness",t)=satt.l(t);
report("pumplift",t)=plift.l(t);
report("pumpcost",t)=pcost.l(t);
report("revenue",t)=NR.l(t);
report("permitp",t)=waterdd.m(t);
display report;
```

GAMS MODEL FOR THE PERMIT TRADING

```
$TITLE  PERMIT MODEL
$OFFUPPER OFFSYMXREF OFFSYMLIST OFFUELLIST OFFUELXREF
OPTION LIMROW=0, LIMCOL=0
OPTION NLP=CONOPT
SETS
t time period /1*20/
a Agents /A1,A2/
k crops /corn,sorghum,cotton,wheat/
tfirst(t)  first period
tlast(t)  last period;
tfirst(t) = yes$(ord(t)eq 1);
tlast(t) = yes$(ord(t) eq card(t));
SCALARS
EF energy use factor for electricity /0.164/
EP energy price /0.09/
EFF pump engine efficiency /0.50/
PSI system operating pressure /16.5/
S  specific yield of the aquifer /0.15/
LA land area overlaying Ogallala /574720/
RECH  recharge rate /0.00001/
IS initial sat thickness of aquifer /79/
ILIFT  initial lift /233/
ICONC initial conc/6.37/
*Farm size  acres
iA1 acres for farm1 /530/
iA2 acres for farm2 /600/
*Well yield in gallons per minute
```

```
WYA1 average well yield for agent A1 /650/
WYA2 average well yield for agent A2/800/
*initial stock rights based on land correlation
*Permits allocated in acre inches per period-above 10000 gallons a day
insA1 initial stock  allocated to agent1/2035/
insA2 initial stock  allocated to agent2/2604/
Pmo price of fertilizer /0.50/
del decay rate of the pollutant/0.10/
eta scaling factor /0.02/
r  discount rate /0.05/;
scalar disc discount;
disc=1/(1+r);
PARAMETER delta discount factor;
delta(t)=(disc**(ord(t)-1));
PARAMETER CP(k) crop prices
*corn $/bu,cotton $/lb sorghum$/bu wheat $/bu
/corn 3.89, cotton 0.56, sorghum 3.47, wheat 5.69/
PARAMETER HC(k) harvest and hauling costs
*corn $/bu, cotton $/lb, sorghum $/bu, wheat $/bu
/corn 0.40, cotton 0.40,sorghum 0.34, wheat 0.50/
PARAMETER LH(k) labor hours allotted per acre
/corn 1.28,cotton 0.77,sorghum 0.89, wheat 0.96/
PARAMETER LC(k) labor costs of irrigation per hour
/corn 10,cotton 10,sorghum 10, wheat 10 /
PARAMETER MC(k) repair and maintenance costs per acre
/corn 2.00,cotton 2.00, sorghum 2.00, wheat 2.00/
PARAMETER FC(k) fixed expenses
/corn 40,cotton 40, sorghum 40, wheat 40/
PARAMETER OP(k) operating costs per acre
/corn 13.52,cotton 14.98, sorghum 8.91, wheat 12.88/
```

```
SCALAR
minwatercor/4/
minwaterc/3/
minwaters/3/
minwaterw/3/
TABLE ac(a,k) land acres for each agent
           corn  cotton sorghum wheat
A1         201    158    37      134
A2         228    180    42      150 ;
*irrigated acres
SCALARirra
irra1/1130/
irra2/963.84/
irra3/959/
irra4/954.16/
irra5/949.33/
irra6/944.49/
irra7/939.65/
irra8/934.81/
irra9/929.97/
irra10/925.13/
irra11/910.61/
irra12/915.45/
irra13/900.93/
irra14/896.09/
irra15/891.25/
irra16/886.41/
irra17/891.25/
irra18/886.41/
irra19/881.57/
irra20/876.73/ ;
```

```
PARAMETER irrlabcA1     ;irrigation labor costs for agent A1
irrlabcA1=sum(k,LH(k)*LC(k)*ac("A1",k))
PARAMETER irrlabcA2     ;irrigation labor costs for agent A2
irrlabcA2=sum(k,LH(k)*LC(k)*ac("A2",k))
PARAMETER fcostA1;fixed costs for agent A1
fcostA1=sum(k,FC(k)*ac("A1",k))
PARAMETER fcostA2;fixed costs for agent A2
fcostA2=sum(k,FC(k)*ac("A2",k))
PARAMETER mcA1;maintenance costs for agent A1
mcA1=sum(k,MC(k)*ac("A1",k))
PARAMETER mcA2;maintenance costs for agent A2
mcA2=sum(k,MC(k)*ac("A2",k))
PARAMETER irracA1; acres irrigated by agent A1
irracA1= sum(k,ac("A1",k))
PARAMETER irracA2; acres irrigated by agent A2
irracA2= sum(k,ac("A2",k))
PARAMETERirrac; total number of irrigated acres
irrac= irracA1+irracA2;

VARIABLES
gyld(a,k,t) yield per acre for crop k
irr(a,k,t) irrigation water applied per acre for crop k
irrtotA1(t) total irrigation water applied by agent A1
irrtotA2(t) total irrigation water applied per acre by agent A1
irrt(t) net irrigation water applied on average
fert(a,k,t) fertilizer applied per acre for crop k
totnfertA1(t) total fertilizer applied by agent A1
totnfertA2(t) total fertilizer applied by agent A2
fertt(t) net fertilizer applied on average
perc(a,k,t) nitrogen percolation below root zone
npercA1(t) total nitrogen percolation for agent A1
npercA2(t) total nitrogen percolation for agent A2
```

```
percl(t) net percolation below root zone
soiln(a,k,t) soil nitrogen per acre for crop k
prk(a,k,t) percolation below root zone for crop k
prec(t) average precipitation
satt(t) saturated thickness
plift(t) pumping lift
hvstcA1(t) net harvest cost for agent A1
hvstcA2(t) net harvest cost for agent A2
*irrlabc  per acre irrigation labor cost
*texpenses(k,t)  per acre irrigation harvest maintenance and fixed costs
nopumpcA1(t) total non pumping costs incurred by agent A1
nopumpcA2(t) total non pumping costs incurred by agent A2
pcost(t) pumping costs incurred
conc(t) concentration of nitrate
stockA1(t) stock of water held by agent A1
stockA2(t) stock of water held by agent A2
permits(t) permits or excess stock
permitp(t) permit price
GPCA1(t) gross pumping capacity for well belonging to A1
GPCA2(t) gross pumping capacity for well belonging to A2
costA1(t) total costs for A1
costA2(t) total costs for A2
NRA1(t) net revenues for A1
NRA2(t) net revenues for A1
NR(t)
NPV;

POSITIVE VARIABLES
irrt(t)
fertt(t)
prec(t)
satt(t)
```

```
plift(t)
permits(t)
pcost(t)
stockA1(t)
stockA2(t)
permits(t)
perc(a,k,t)
perct(t)
npercA1(t)
npercA2(t)
prec
EQUATIONS
yieldc(a,t) yield equation for cotton per acre
yieldcor(a,t)yield equation for corn per acre
yields(a,t)yield equation for sorghum per acre
yieldw(a,t)yield equation for wheat per acre
thvstcA1(t) harvest cost equation for A1
thvstcA2(t) harvest cost equation for A2
tnopumpcA1(t) non pumping cost equation for A1
tnopumpcA2(t) non pumping cost equation for A2
waterddA1(t) equation for net water use by A1
waterddA2(t) equation for net water use by A2
totwdd(t) equation for net water use on average
tfertA1(t) equation for net fertilizer use by A1
tfertA2(t) equation for net fertilizer use by A2
totfert(t) equation for net fertilizer use on average
tcostA1(t) total costs incurred by A1
tcostA2(t) total costs incurred by A2

*Equations for minimum input requiremnets
minirrcor(a,t)
minirrc(a,t)
```

```
minirrs(a,t)
minirrw(a,t)
minfertcor(a,t)
minferts(a,t)
minfertc(a,t)
minfertw(a,t)

npercсor(a,t) percolation equation per acre for corn
npercc(a,t) percolation equation per acre for cotton
npercs(a,t) percolation equation per acre for sorghum
npercw(a,t) percolation equation per acre for wheat
totpercA1(t) percolation equation valid for A1
totpercA2(t) percolation equation valid for A2
perctot(t) percolation total
netrevA1(t) net revenues for A1
netrevA2(t) net revenues for A2
stockbA1(t) stock equation for A1
stockbA2(t) stock equation for A2
pcapacityA1(t) pumping capacity equation for A1
pcapacityA2(t) pumping capacity equation for A2
pss(t) supply of permits
stockbA11 stock equation for A1 in the first period
stockbA21 stock equation for A2 in the first period
plimitA1(t) pumping limit for A1
*plimitA2(t) pumping limit for A2

*EQUATION FOR SATURATED THICKNESS
sat1
sat2
sat3
sat4
sat5
```

```
sat6
sat7
sat8
sat9
sat10
sat11
sat12
sat13
sat14
sat15
sat16
sat17
sat18
sat19
*PUMPING LIFT TRANSITION EQUATION
lift1
lift2
lift3
lift4
lift5
lift6
lift7
lift8
lift9
lift10
lift11
lift12
lift13
lift14
lift15
lift16
lift17
```

```
lift18

lift19

*PUMPING COST EQUATIONS

pumpc(t)

nconc(t) nitrate conc transition equation

rev(t)

obj;

*YIELD EQUATIONS

yieldcor(a,t)..gyld(a,"corn",t)=E=77.22+0.035*(irr(a,"corn",t)*fert(a,"c
orn",t))-0.00000275*(irr(a,"corn",t)*fert(a,"corn",t))**2;

yieldc(a,t)..gyld(a,"cotton",t)=E=530.68+0.79*(irr(a,"cotton",t)*fert(a,
"cotton",t))-0.0002*(irr(a,"cotton",t)*fert(a,"cotton",t))**2;

yields(a,t)..gyld(a,"sorghum",t)=E=28.94+0.044*(irr(a,"sorghum",t)*fert(
a,"sorghum",t))-0.0000064*(irr(a,"sorghum",t)*fert(a,"sorghum",t))**2;

yieldw(a,t)..gyld(a,"wheat",t)=E=13.22+0.006*(irr(a,"wheat",t)*fert(a,"w
heat",t))-0.00000252*(irr(a,"wheat",t)*fert(a,"wheat",t))**2;

*COST EQUATIONS

thvstcA1(t)..hvstcA1(t)=E=sum(k,hc(k)*gyld("A1",k,t)*ac("A1",k));

thvstcA2(t)..hvstcA2(t)=E=sum(k,hc(k)*gyld("A2",k,t)*ac("A2",k));


*thvstcA1(t)..hvstcA1(t)=E=(hc("corn")*gyld("A1","corn",t)*la("A1","corn
"))+(hc("cotton")*gyld("A1","cotton",t)*la("A1","cotton"))+(hc("sorghum"
)*gyld("A1","sorghum",t)*la("A1","sorghum"))+(hc("wheat")*gyld("A1","whe
at",t)*la("A1","wheat"));

*thvstcA2(t)..hvstcA2(t)=E=(hc("corn")*gyldcor("A2","corn",t)*la("A2","c
orn"))+(cothc*gyldc("A2",t)*cotacA1)+(sorhc*gylds("A2",t)*soracA1)+(whhc
*gyldw("A2",t)*whacA1);

tnopumpcA1(t)..nopumpcA1(t)=E=irrlabcA1+hvstcA1(t)+mcA1+fcostA1;

tnopumpcA2(t)..nopumpcA2(t)=E=irrlabcA2+hvstcA2(t)+mcA2+fcostA2;


*INPUT DEMAND EQUATIONS

waterddA1(t)..sum(k,irr("A1",k,t)*ac("A1",k))=G=irrtotA1(t);

waterddA2(t)..sum(k,irr("A2",k,t)*ac("A2",k))=L=irrtotA2(t);

totwdd(t)..irrt(t)=E=(irrtotA1(t)*irracA1+irrtotA2(t)*irracA2)/irrac;
```

```
tfertA1(t)..sum(k,fert("A1",k,t)*ac("A1",k))/irracA1=E=totnfertA1(t);

tfertA2(t)..sum(k,fert("A2",k,t)*ac("A2",k))/irracA2=E=totnfertA2(t);

*Add fert use for both farms for all acres

totfert(t)..fertt(t)=E=(totnfertA1(t)*irracA1+totnfertA2(t)*irracA2)/irr
ac;

tcostA1(t)..
costA1(t)=E=pcost(t)+nopumpcA1(t)+(Pmo*totnfertA1(t)*irracA1);

tcostA2(t)..
costA2(t)=E=pcost(t)+nopumpcA2(t)+(Pmo*totnfertA2(t)*irracA2);


minirrcor(a,t)..irr(a,"corn",t)=G= minwatercor;

minirrc(a,t)..irr(a,"cotton",t)=G= minwaterc;

minirrs(a,t)..irr(a,"sorghum",t)=G= minwaters;

minirrw(a,t)..irr(a,"wheat",t)=G= minwaterw;

minfertcor(a,t)..fert(a,"corn",t)=G=119.98;

minferts(a,t)..fert(a,"sorghum",t)=G=85.7;

minfertc(a,t)..fert(a,"cotton",t)=G=49.63;

minfertw(a,t)..fert(a,"wheat",t)=G=108.27;


*EQUATIONS FOR SATURATED THICKNESS

sat1..satt("2")=E=satt("1")-((irrt("1")-RECH)*irra1/12)/(S*LA);

sat2..satt("3")=E=satt("2")-((irrt("2")-RECH)*irra2/12)/(S*LA);

sat3..satt("4")=E=satt("3")-((irrt("3")-RECH)*irra3/12)/(S*LA);

sat4..satt("5")=E=satt("4")-((irrt("4")-RECH)*irra4/12)/(S*LA);

sat5..satt("6")=E=satt("5")-((irrt("5")-RECH)*irra5/12)/(S*LA);

sat6..satt("7")=E=satt("6")-((irrt("6")-RECH)*irra6/12)/(S*LA);

sat7..satt("8")=E=satt("7")-((irrt("7")-RECH)*irra7/12)/(S*LA);

sat8..satt("9")=E=satt("8")-((irrt("8")-RECH)*irra8/12)/(S*LA);

sat9..satt("10")=E=satt("9")-((irrt("9")-RECH)*irra9/12)/(S*LA);

sat10..satt("11")=E=satt("10")-((irrt("10")-RECH)*irra10/12)/(S*LA);

sat11..satt("12")=E=satt("11")-((irrt("11")-RECH)*irra11/12)/(S*LA);

sat12..satt("13")=E=satt("12")-((irrt("12")-RECH)*irra12/12)/(S*LA);

sat13..satt("14")=E=satt("13")-((irrt("13")-RECH)*irra13/12)/(S*LA);
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```
sat14..satt("15")=E=satt("14")-((irrt("14")-RECH)*irra14/12)/(S*LA);
sat15..satt("16")=E=satt("15")-((irrt("15")-RECH)*irra15/12)/(S*LA);
sat16..satt("17")=E=satt("16")-((irrt("16")-RECH)*irra16/12)/(S*LA);
sat17..satt("18")=E=satt("17")-((irrt("17")-RECH)*irra17/12)/(S*LA);
sat18..satt("19")=E=satt("18")-((irrt("18")-RECH)*irra18/12)/(S*LA);
sat19..satt("20")=E=satt("19")-((irrt("19")-RECH)*irra19/12)/(S*LA);

*EQUATIONS FOR PUMPING LIFT
lift1..plift("2")=E=plift("1")+((irrt("1")-RECH)*irra1/12)/(LA*S);
lift2..plift("3")=E=plift("2")+((irrt("2")-RECH)*irra2/12)/(LA*S);
lift3..plift("4")=E=plift("3")+((irrt("3")-RECH)*irra3/12)/(LA*S);
lift4..plift("5")=E=plift("4")+((irrt("4")-RECH)*irra4/12)/(LA*S);
lift5..plift("6")=E=plift("5")+((irrt("5")-RECH)*irra5/12)/(LA*S);
lift6..plift("7")=E=plift("6")+((irrt("6")-RECH)*irra6/12)/(LA*S);
lift7..plift("8")=E=plift("7")+((irrt("7")-RECH)*irra7/12)/(LA*S);
lift8..plift("9")=E=plift("8")+((irrt("8")-RECH)*irra8/12)/(LA*S);
lift9..plift("10")=E=plift("9")+((irrt("9")-RECH)*irra9/12)/(LA*S);
lift10..plift("11")=E=plift("10")+((irrt("10")-RECH)*irra10/12)/(LA*S);
lift11..plift("12")=E=plift("11")+((irrt("11")-RECH)*irra11/12)/(LA*S);
lift12..plift("13")=E=plift("12")+((irrt("12")-RECH)*irra12/12)/(LA*S);
lift13..plift("14")=E=plift("13")+((irrt("13")-RECH)*irra13/12)/(LA*S);
lift14..plift("15")=E=plift("14")+((irrt("14")-RECH)*irra14/12)/(LA*S);
lift15..plift("16")=E=plift("15")+((irrt("15")-RECH)*irra15/12)/(LA*S);
lift16..plift("17")=E=plift("16")+((irrt("16")-RECH)*irra16/12)/(LA*S);
lift17..plift("18")=E=plift("17")+((irrt("17")-RECH)*irra17/12)/(LA*S);
lift18..plift("19")=E=plift("18")+((irrt("18")-RECH)*irra18/12)/(LA*S);
lift19..plift("20")=E=plift("19")+((irrt("19")-RECH)*irra19/12)/(LA*S);

*EQUATIONS FOR PUMPING COST
pumpc(t)..pcost(t)=E=((EF*(plift(t)+2.31*PSI)*EP)/EFF)*irrt(t);


pcapacityA1(t)..GPCA1(t)=E=4.42*(WYA1)*(satt(t)/IS)**2;
```

```
pcapacityA2(t)..GPCA2(t)=E=4.42*(WYA2)*(satt(t)/IS)**2;


*For the first year
stockbA11..stockA1("1")=E=insA1+GPCA1("1");
stockbA21..stockA2("1")=E=insA2+GPCA2("1");
pss(t)..permits(t)=E=(stockA2(t)-irrtotA2(t)*irracA2);


*second year onwards
stockbA1(t)$(ord(t)GE 1)..stockA1(t+1)=E=stockA1(t)+0.30*permits(t)-
irrtotA1(t)*irracA1;
stockbA2(t)$(ord(t)GT1)..stockA2(t+1)=E=stockA2(t)-irrtotA2(t)*irracA2;


plimitA1(t)..irrtotA1(t)*irracA1=L=stockA1(t)+0.30*permits(t);
*PERCOLATION EQUATIONS
nperccor(a,t)..perc(a,"corn",t)=E=-
0.32+0.20*prk(a,"corn",t)+0.009*prec(t)-0.007*gyld(a,"corn",t)-
0.004*soiln(a,"corn",t)-0.029*irr(a,"corn",t)+0.011*fert(a,"corn",t);
npercc(a,t)..perc(a,"cotton",t)=E=1.91+31.18*prk(a,"cotton",t)-
5.77*prec(t)-0.12*gyld(a,"cotton",t)-0.06*soiln(a,"cotton",t)-
17.28*irr(a,"cotton",t)+2.09*fert(a,"cotton",t);
npercs(a,t)..perc(a,"sorghum",t)=E=-
11.09+0.228*prk(a,"sorghum",t)+1.031*prec(t)-0.264*gyld(a,"sorghum",t)-
0.897*soiln(a,"sorghum",t)+0.235*irr(a,"sorghum",t)+0.705*fert(a,"sorghu
m",t);
npercw(a,t)..perc(a,"wheat",t)=E=47.47+1.76*prk(a,"wheat",t)-
4.918*prec(t)-2.269*gyld(a,"wheat",t)-0.218*soiln(a,"wheat",t)-
13.62*irr(a,"wheat",t)+1.296*fert(a,"wheat",t);
totpercA1(t)..sum(k,perc("A1",k,t)*ac("A1",k))/irracA1=E=npercA1(t);
totpercA2(t)..sum(k,perc("A2",k,t)*ac("A2",k))/irracA2=E=npercA2(t);
perctot(t)..perct(t)=E=(npercA1(t)*irracA1+npercA2(t)*irracA2)/irrac;
*NITRATE CONCENTRATION EQUATIONS
nconc(t)..conc(t+1)=E=(1-del)*conc(t)+eta*perct(t);
*NET REVENUE EQUATIONS
netrevA1(t)..NRA1(t)=E=sum(k,CP(k)*gyld("A1",k,t)*ac("A1",k))-costA1(t)-
permitp(t)*0.30*permits(t);
```

```
netrevA2(t)..NRA2(t)=E=sum(k,CP(k)*gyld("A2",k,t)*ac("A2",k))-
costA2(t)+permitp(t)*0.30*permits(t);


rev(t)..NR(t)=E=NRA1(t)+NRA2(t);

obj..NPV=E=sum(t,NR(t)*delta(t));


plift.lo(t)=ILIFT;

plift.fx(tfirst(t))=plift.lo(t);

conc.lo(t)=0.01;

conc.fx(tfirst(t))=ICONC;

satt.fx(tfirst(t))=IS;

*PERMIT PRICES

permitp.fx("1")=0.30;permitp.fx("2")=0.30;permitp.fx("3")=0.30;permitp.f
x("4")=0.30;permitp.fx("5")=0.30;permitp.fx("6")=0.30;permitp.fx("7")=0.
30;permitp.fx("8")=0.30;permitp.fx("9")=0.30;permitp.fx("10")=0.30;permi
tp.fx("11")=0.30;permitp.fx("12")=0.30;permitp.fx("13")=0.30;permitp.fx(
"14")=0.29;permitp.fx("15")=0.25;permitp.fx("16")=0.20;permitp.fx("17")=
0.15;permitp.fx("18")=0.30;permitp.fx("19")=0.52;permitp.fx("20")=0.52;


prk.fx(a,"sorghum",t)=57.43;

soiln.fx(a,"sorghum",t)=3.467;

prk.fx(a,"cotton",t)=1.12;

soiln.fx(a,"cotton",t)=49.12;

prk.fx(a,"wheat",t)=61.92;

soiln.fx(a,"wheat",t)=69.78;

prk.fx(a,"corn",t)=0.863;

soiln.fx(a,"corn",t)=64.08;


*Average values simulated

fert.up(a,"corn",t)=155.38;

fert.up(a,"sorghum",t)=115.81;

fert.up(a,"cotton",t)=90.16;


irr.up(a,"sorghum",t)=10;
```

```
irr.up(a,"corn",t)=12;
irr.up(a,"cotton",t)=16;
*irrw.up(a,t)=20;
model permit/all/;
parameter report(*,*);
Solve permit maximizing NPV using nlp;
report("CornyldA1",t)=gyld.l("A1","corn",t);
report("CornyldA1",t)=gyld.l("A2","corn",t);
report("SoryldA1",t)=gyld.l("A1","sorghum",t);
report("SoryldA2",t)=gyld.l("A2","sorghum",t);
report("CottyldA1",t)=gyld.l("A1","cotton",t);
report("CottyldA2",t)=gyld.l("A2","cotton",t);
report("wheatyldA1",t)=gyld.l("A1","wheat",t);
report("wheatyldA2",t)=gyld.l("A2","wheat",t);
report("totfertA1",t)=totnfertA1.l(t);
report("totfertA2",t)=totnfertA2.l(t);
report("totirrA1",t)=irrtotA1.l(t);
report("totirrA2",t)=irrtotA2.l(t);
report("nitconc",t)=conc.l(t);
report("satthickness",t)=satt.l(t);
report("pumplift",t)=plift.l(t);
report("pumpcost",t)=pcost.l(t);
report("revenueA1",t)=NRA1.l(t);
report("revenueA2",t)=NRA2.l(t);
display report;
```

GAMS MODEL FOR THE MYOPIC AGENT

```
$TITLE  MYOPIC MODEL
*Agent 1 model with competitive extraction
*Maximizes own income w/o concern about the extraction rates on
future pumping and thus on the pumping costs and water level
$OFFUPPER OFFSYMXREF OFFSYMLIST OFFUELLIST OFFUELXREF
OPTION LIMROW=0, LIMCOL=0
OPTION NLP=CONOPT
SETS
t time period /1*20/
k crops /corn,sorghum,cotton,wheat/
tfirst(t)  first period
tlast(t)  last period;
tfirst(t) = yes$(ord(t)eq 1);
tlast(t) = yes$(ord(t) eq card(t));
SCALARS
EF energy use factor for electricity /0.164/
EP energy price /0.09/
EFF pump engine efficiency /0.50/
PSI system operating pressure /16.5/
S  specific yield of the aquifer /0.15/
A land area overlaying Ogallala /574720/
*Obtained from the joint maximization problem
MCo cost per acre inch of water drawn per unit of lift /0.04/
RECH  recharge rate /0.00001/
IS initial sat thickness of aquifer /79/
SL /242/
ILIFT  initial lift /233/
ICONC initial conc/6.37/

*Well yield in gallons per minute
```

```
WY average well yield /650/
Pmo price of nit fertilizer /0.50/
del decay rate/0.10/
eta scaling factor /0.02/
r  discount rate /0.05/;
scalar disc discount;
disc=1/(1+r);
PARAMETER delta discount factor;
delta(t)=(disc**(ord(t)-1));
PARAMETER CP(k) crop prices
*corn $/bu,cotton $/lb sorghum$/bu wheat $/bu
/corn 3.89, cotton 0.56, sorghum 3.47, wheat 5.69/
PARAMETER HC(k) harvest and hauling costs
*corn $/bu, cotton $/lb, sorghum $/bu, wheat $/bu
/corn 0.40, cotton 0.40,sorghum 0.34, wheat 0.50/
PARAMETER LH(k) labor hours allotted per acre
/corn 1.28,cotton 0.77,sorghum 0.89, wheat 0.96/
PARAMETER LC(k) labor costs of irrigation per hour
/corn 10,cotton 10,sorghum 10, wheat 10 /
PARAMETER MC(k) repair and maintenance costs per acre
/corn 2.00,cotton 2.00, sorghum 2.00, wheat 2.00/
PARAMETER FC(k) fixed expenses
/corn 40,cotton 40, sorghum 40, wheat 40/
PARAMETERirrla(k) irrigated land acreage for crops
/corn 201,cotton 158, sorghum 37, wheat 134/;
SCALARS
Minirrcor minimum irrigation water requirements for corn /4/
minirrcot minimum irrigation water requirements for cotton/3/
minirrs minimum irrigation water requirements for sorghum/4/
minirrw minimum irrigation water requirements for wheat /4/;

SCALAR disc discount;
disc=1/(1+r);
PARAMETER delta discount factor;
delta(t)=(disc**(ord(t)-1))
```

```
PARAMETER irrlabc     ;
irrlabc=sum(k,LH(k)*LC(k))
PARAMETER fcost;
fcost=sum(k,FC(k))
PARAMETER irrac;
irrac= sum(k,irrla(k));
*actual trend forecast
SCALARia irrigated acres
ia1 /530/
ia2/530.12/
ia3/527.45/
ia4/524.79/
ia5/522.13/
ia6/519.44/
ia7/516.81/
ia8/514.14/
ia9/511.48/
ia10/508.82/
ia11/506.16/
ia12/503.49/
ia13/500.84/
ia14/498.17/
ia15/495.51/
ia16/492.85/
ia17/490.19/
ia18/487.53/
ia19/484.86/
ia20/482.20/ ;
VARIABLES x
gyld(k,t) grain yield per acre for crop k
irr(k,t) irrigation water applied per acre for crop k

fert(k,t) fertilizer applied per acre for crop k

irrtot(t) net irrigation water applied per acre
```

```
totnfert(t) net fertilizer applied per acre

perc(k,t) percolation of nutrient for crop k

nperc(t) weighted average of percolation of nitrogen fertilizer
soiln(k,t) soil nitrogen available per acre for crop k

prk(k,t)percolation below root zone for crop k

prec(t) precipitation level
conc(t) nitrate concentration
hvstc(t) harvest and hauling costs
mpcost(t) marginal pumping cost
mcost(t)
nopumpcost(t) total cost without pumping costs
pcost(t) pumping cost per acre inch
cost(t) total costs incurred
satt(t) saturated thickness of aquifer in the county
plift(t) pumping lift of the aquifer

GPC(t) gross pumping capacity of the aquifer
pwater(t)
NR(t) net revenues
NPV net present value of production/ benefits
POSITIVE VARIABLES x
perc(k,t)
nperc(t)
EQUATIONS
yieldcor(t) yield equation for corn per acre

yieldc(t)yield equation for cotton per acre
yields(t)yield equation for sorghum per acre

yieldw(t)yield equation for wheat per acre

waterdd(t) water use equation per acre

fertappl(t) fertilizer use equation per acre
```

nperccor(t) percolation equation for corn
npercs(t) percolation equation for sorghum
npercw(t) percolation equation for wheat
npercc(t) percolation equation for cotton

totperc(t) total percolation equation

*COST EQUATIONS
thvstc(t) total harvest and hauling cost equation
tmc(t)total maintenance cost equation

mpc(t) marginal pumping cost equation
pc(t) pumping cost equation
tnopumpc(t)total nonpumping cost equation

tcost(t) total cost equation

pcapacity(t) pumping capacity equation

*MINIMUM INPUT USE EQUATIONS

mirrcor(t)
mirrs(t)
mirrc(t)
mirrw(t)
mfertcor(t)
mferts(t)
mfertc(t)
mfertw(t)

netrev(t) net returns from production
obj maximizing discounted net returns
*PUMPING LIFT TRANSITION EQUATIONS
lift1
lift2

```
lift3
lift4
lift5
lift6
lift7
lift8
lift9
lift10
lift11
lift12
lift13
lift14
lift15
lift16
lift17
lift18
lift19

*EQUATIONS FOR SATURATED THICKNESS
sat1
sat2
sat3
sat4
sat5
sat6
sat7
sat8
sat9
sat10
sat11
sat12
sat13
sat14
sat15
sat16
```

```
sat17
sat18
sat19
*NITRATE CONC TRANSITION EQUATION
nconc(t)
*WATER USE EQUATION
waterdd(t);
*YIELD EQUATIONS
yieldcor(t)..gyld("corn",t)=E=-
120.783+15.991*irr("corn",t)+0.4767*fert("corn",t)-
0.37981*irr("corn",t)**2-
0.0000578*fert("corn",t)**2+0.02163*(irr("corn",t)*fert("corn",t)
)**2;
yieldc(t)..gyld("cotton",t)=E=530.68+0.79*(irr("cotton",t)*fert("
cotton",t))-0.0002*(irr("cotton",t)*fert("cotton",t))**2;
yields(t)..gyld("sorghum",t)=E=28.94+0.044*(irr("sorghum",t)*fert
("sorghum",t))-0.0000064*(irr("sorghum",t)*fert("sorghum",t))**2;
yieldw(t)..gyld("wheat",t)=E=13.22+0.006*(irr("wheat",t)*fert("wh
eat",t))-0.00000252*(irr("wheat",t)*fert("wheat",t))**2;
*COST EQUATIONS
thvstc(t)..hvstc(t)=E=sum(k,hvstc(t)*gyld(k,t));
mpc(t)..mpcost(t)=E=MCo*(SL-plift(t));
pc(t)..pcost(t)=E=(mpcost(t)*irrtot(t));
tmc(t)..mcost(t)=E=sum(k,MC(k)*irr(k,t));
tnopumpc(t)..nopumpcost(t)=E=(irrlabc+hvstc(t)+fcost+mcost(t));
tcost(t).. cost(t)=E=pcost(t)+Pmo*totnfert(t)+nopumpcost(t);
waterdd(t)..irrtot(t)=E=sum(k,irr(k,t)*irrla(k))/irrac;
fertappl(t)..totnfert(t)=E=sum(k,fert(k,t)*irrla(k))/irrac;

mirrcor(t)..irr("corn",t)=G=minirrcor;
mirrs(t)..irr("sorghum",t)=G=minirrs;
mirrc(t)..irr("cotton",t)=G=minirrcot;
mirrw(t)..irr("wheat",t)=G=minirrw;
mfertcor(t)..fert("corn",t)=G=119.98;
mferts(t)..fert("sorghum",t)=G=85.7;
```

```
mfertc(t)..fert("cotton",t)=G=49.63;
mfertw(t)..fert("wheat",t)=G=108.27;
*REVENUE EQUATION
netrev(t)..NR(t)=E=sum(k,CP(k)*gyld(k,t)*irrla(k))-cost(t);
obj.. NPV=E=sum(t,NR(t)*delta(t));
*PUMPING LIFT EQUATIONS
lift1..plift("2")=E=plift("1")+((irrtot("1")-RECH)*ia1/12)/(A*S);
lift2..plift("3")=E=plift("2")+((irrtot("2")-RECH)*ia2/12)/(A*S);
lift3..plift("4")=E=plift("3")+((irrtot("3")-RECH)*ia3/12)/(A*S);
lift4..plift("5")=E=plift("4")+((irrtot("4")-RECH)*ia4/12)/(A*S);
lift5..plift("6")=E=plift("5")+((irrtot("5")-RECH)*ia5/12)/(A*S);
lift6..plift("7")=E=plift("6")+((irrtot("6")-RECH)*ia6/12)/(A*S);
lift7..plift("8")=E=plift("7")+((irrtot("7")-RECH)*ia7/12)/(A*S);
lift8..plift("9")=E=plift("8")+((irrtot("8")-RECH)*ia8/12)/(A*S);
lift9..plift("10")=E=plift("9")+((irrtot("9")-
RECH)*ia9/12)/(A*S);
lift10..plift("11")=E=plift("10")+((irrtot("10")-
RECH)*ia10/12)/(A*S);
lift11..plift("12")=E=plift("11")+((irrtot("11")-
RECH)*ia11/12)/(A*S);
lift12..plift("13")=E=plift("12")+((irrtot("12")-
RECH)*ia12/12)/(A*S);
lift13..plift("14")=E=plift("13")+((irrtot("13")-
RECH)*ia13/12)/(A*S);
lift14..plift("15")=E=plift("14")+((irrtot("14")-
RECH)*ia14/12)/(A*S);
lift15..plift("16")=E=plift("15")+((irrtot("15")-
RECH)*ia15/12)/(A*S);
lift16..plift("17")=E=plift("16")+((irrtot("16")-
RECH)*ia16/12)/(A*S);
lift17..plift("18")=E=plift("17")+((irrtot("17")-
RECH)*ia17/12)/(A*S);
lift18..plift("19")=E=plift("18")+((irrtot("18")-
RECH)*ia18/12)/(A*S);
```

```
lift19..plift("20")=E=plift("19")+((irrtot("19")-
RECH)*ia19/12)/(A*S);
*PERCOLATION EQUATIONS
nperccor(t)..perc("corn",t)=E=-
0.04+0.20*prk("corn",t)+0.009*prec(t)-0.007*gyld("corn",t)-
0.004*soiln("corn",t)-0.029*irr("corn",t)+0.011*fert("corn",t);
npercc(t)..perc("cotton",t)=E=1.91+31.18*prk("cotton",t)-
5.77*prec(t)-0.12*gyld("cotton",t)-0.06*soiln("cotton",t)-
17.28*irr("cotton",t)+2.09*fert("cotton",t);
npercs(t)..perc("sorghum",t)=E=28.94+0.228*prk("sorghum",t)+1.031
*prec(t)-0.264*gyld("sorghum",t)-
0.897*soiln("sorghum",t)+0.235*irr("sorghum",t)+0.705*fert("sorgh
um",t);
npercw(t)..perc("wheat",t)=E=47.47+1.76*prk("wheat",t)-
4.918*prec(t)-2.269*gyld("wheat",t)-0.218*soiln("wheat",t)-
13.62*irr("wheat",t)+1.296*fert("wheat",t);
totperc(t)..nperc(t)=E=sum(k,perc(k,t)*irrla(k))/irrac;
nconc(t)..conc(t+1)=E=(1-del)*conc(t)+eta*nperc(t);

*SATURATED THICKNESS EQUATIONS
sat1..satt("2")=E=satt("1")-((irrtot("1")-RECH)*ia1/12)/(S*A);
sat2..satt("3")=E=satt("2")-((irrtot("2")-RECH)*ia2/12)/(S*A);
sat3..satt("4")=E=satt("3")-((irrtot("3")-RECH)*ia3/12)/(S*A);
sat4..satt("5")=E=satt("4")-((irrtot("4")-RECH)*ia4/12)/(S*A);
sat5..satt("6")=E=satt("5")-((irrtot("5")-RECH)*ia5/12)/(S*A);
sat6..satt("7")=E=satt("6")-((irrtot("6")-RECH)*ia6/12)/(S*A);
sat7..satt("8")=E=satt("7")-((irrtot("7")-RECH)*ia7/12)/(S*A);
sat8..satt("9")=E=satt("8")-((irrtot("8")-RECH)*ia8/12)/(S*A);
sat9..satt("10")=E=satt("9")-((irrtot("9")-RECH)*ia9/12)/(S*A);
sat10..satt("11")=E=satt("10")-((irrtot("10")-
RECH)*ia10/12)/(S*A);
sat11..satt("12")=E=satt("11")-((irrtot("11")-
RECH)*ia11/12)/(S*A);
sat12..satt("13")=E=satt("12")-((irrtot("12")-
RECH)*ia12/12)/(S*A);
```

```
sat13..satt("14")=E=satt("13")-((irrtot("13")-
RECH)*ia13/12)/(S*A);
sat14..satt("15")=E=satt("14")-((irrtot("14")-
RECH)*ia14/12)/(S*A);
sat15..satt("16")=E=satt("15")-((irrtot("15")-
RECH)*ia15/12)/(S*A);
sat16..satt("17")=E=satt("16")-((irrtot("16")-
RECH)*ia16/12)/(S*A);
sat17..satt("18")=E=satt("17")-((irrtot("17")-
RECH)*ia17/12)/(S*A);
sat18..satt("19")=E=satt("18")-((irrtot("18")-
RECH)*ia18/12)/(S*A);
sat19..satt("20")=E=satt("19")-((irrtot("19")-
RECH)*ia19/12)/(S*A);
*pcapacity(t)..GPC(t)=E=28.25*((satt(t)*12)/210)**2;
pcapacity(t)..GPC(t)=E=4.42*(WY)*(satt(t)*12/IS)**2;
*plimit(t)..irrtot(t)=L=GPC(t);
*INITIALIZATION
plift.lo(t)=ILIFT;
plift.fx(tfirst(t))=plift.lo(t);
conc.lo(t)=0.01;
conc.fx(tfirst(t))=ICONC;
satt.fx(tfirst(t))=IS;

prk.fx("corn",t)=0.863;
prec.fx(t)=13.14;
soiln.fx("corn",t)=64.08;
prk.fx("cotton",t)=1.12;
soiln.fx("cotton",t)=49.12;
prk.fx("sorghum",t)=57.43;
soiln.fx("sorghum",t)=3.467;
prk.fx("wheat",t)=61.92;
soiln.fx("wheat",t)=69.78;
```

```
*BOUNDS
fert.up("corn",t)=155.38;
model myopic/all/;
PARAMETER REPORT(*,*);
Solve myopic maximizing NPV using nlp;
report("Cornyld",t)=gyld.l("corn",t);
report("Soryld",t)=gyld.l("sorghum",t);
report("Cottyld",t)=gyld.l("cotton",t);
report("wheatyld",t)=gyld.l("wheat",t);
report("totfert",t)=totnfert.l(t);
report("totirr",t)=irrtot.l(t);
report("nitconc",t)=conc.l(t);
report("satthickness",t)=satt.l(t);
report("pumplift",t)=plift.l(t);
report("pumpcost",t)=pcost.l(t);
report("revenue",t)=NR.l(t);
display report;
```

VITA

Sanchari Ghosh

Candidate for the Degree of

Doctor of Philosophy

Thesis: ISSUES INVOLVED IN GROUNDWATER WITHDRAWALS AND POLLUTION OF THE OGALLALA: EVIDENCE FROM WEST TEXAS

Major Field: Economics

Biographical:

Education: Completed the requirements for the Doctor of Philosophy in Economics at Oklahoma State University, Stillwater, Oklahoma in May, 2012. Completed the requirements for the Master of Science in Economics at Calcutta University, Calcutta, West Bengal, India in September 2003. Completed the requirements for the Bachelor of Science in Economics at Calcutta University, Calcutta, West Bengal, India in September 2001.

Experience: Graduate Research Assistant at Oklahoma State University, Stillwater, Oklahoma from Aug 2008-May 2012. Graduate Research Associate at Oklahoma State University, Stillwater, Oklahoma from Jan 2008-May 2008. Graduate Teaching Associate at Oklahoma State University, Stillwater, Oklahoma from Aug 2006-Dec 2007.

Professional Memberships: Association of Environmental and Resource Economists, Southern Economic Association, Golden Key International Honor Society

Name: Sanchari Ghosh Date of Degree: May, 2012

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: ISSUES INVOLVED IN GROUNDWATER WITHDRAWALS AND POLLUTION OF THE OGALLALA: EVIDENCE FROM WEST TEXAS

Pages in Study: 215 Candidate for the Degree of Doctorate of Philosophy

Major Field: Economics

Scope and Method of Study: The existing body of economic research dealing with groundwater extraction seems to focus only on that problem itself and does not view the exploitation of the aquifer and the corresponding pollution problem as a joint resource issue. This research attempts to fill in this gap, with the main objective being to assess the economic tradeoffs involved in groundwater quantity and quality management by capturing the dynamic behavior of the stock of groundwater as well as the stock of pollutant over a twenty year time period. The study uses simulated data for the estimation of production functions and nitrogen percolation functions and those estimates are used in a dynamic optimization framework to find out the level of water and nitrogen fertilizer applied per acre that maximizes net present value over a twenty year planning horizon.

Findings and Conclusions: Two sets of policies are developed for the joint management of groundwater quantity and quality and to evaluate the effect on the net present value of production. First a constraint is imposed on the use of nitrogen fertilizer per acre and then the price of nitrogen fertilizer is raised successively by 5% and 10%. Findings for Castro County in West Texas, point towards a favorable impact on groundwater quality whenever this practice of restricting the use of the polluting input is implemented. Secondly, certain policies aimed at raising the volume of water in storage along with maintaining some level of water quality are implemented. For Castro County, restriction on the terminal value of saturated thickness (or the water table) as well as buying out water rights show a 7 and 4 mg/l increase in the stock of pollutant with a saturated thickness decline by 6 feet less than the base level. However, the same policies have moderate impact upon water use and quality in Lubbock County which may point towards site specific policy recommendations. The research concludes with a proposed agent based trading scenario on the lines of Vernon Smith's water deeds approach where two agents using the same inputs for production are allowed to trade after allocation of an initial set of permits for water withdrawal. The impact on the level and quality of water as well as the individual net revenues turns out to be superior when compared to a purely myopic policy of extracting as much of the inputs as possible.

ADVISER'S APPROVAL: Dr. Keith Willett