2012
OKSWP1201

Economics Working Paper Series
OKLAHOMA STATE UNIVERSITY

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JEL Classifications: Q1, Q3

(April, 2012)

Abstract: *The High Plains region in West Texas has been the focus of water conservation policies for the last two decades because of rapid depletion of groundwater in this region. Groundwater is the only source of irrigation in this region of Texas with Ogallala serving as the major aquifer. In recent times, however, attention has been drawn on nitrate pollution of the Ogallala aquifer, though no study or research report has come up with a joint management solution to cope with both of these problems. This research attempts to fill this gap, taking the rural county of Castro as a case study. The main objective is to make an empirical assessment of this tradeoff by capturing the dynamic behavior of the stock of groundwater as well as the stock of pollutant over a twenty year period. 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 a constraint is imposed on the use of nitrogen fertilizer per acre; second, the price of nitrogen fertilizer is raised successively by 5% and 10%. Secondly, certain policies aimed at raising the volume of water in storage such as restricting the use of irrigation water by around 0.50 acre-inch per acre from the base solution as well as buying out water rights also show positive results in terms of water quantity and quality. 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.*

Keywords: Extraction, pollution, constraint, quota, buyout

1. Introduction

The High Plains region of West Texas has long been served by the Ogallala Aquifer as a source water. Irrigated agriculture constitutes almost 95 percent of groundwater use in a majority of the counties in the region. The heavy reliance on the Ogallala over the years has set in motion a long term trend of depleting the aquifer. This trend has motivated a series of policy discussions where the primary objective has been to identify an appropriate set of management strategies to encourage rational pumping among agents and limit the long-term depletion of the aquifer. In the past few years, concerns have been raised about pollution in the Ogallala Aquifer, particularly due to pesticides and fertilizers used with agricultural activities. For example, some counties of the High Plains, viz. Lynn, Lubbock, Hockley, Lamb, etc., nitrate concentrations well above 10mg/l were reported in a study by Hudak (2000) as well as by investigations carried out by the Texas Water Resources Board. A USGS Scientific Investigations Report by Gurdak and Qi

(2006) puts groundwater contamination levels slightly above drinking water standards.[1] (The maximum concentration level of nitrates acceptable as safe as per EPA drinking water standards is 10mg/l). This study will focus on the water management and nitrate pollution aspect of the Ogallala aquifer by targeting nitrogen leaching during crop production in the rural county of Castro in West Texas. *The reason Castro County is selected for two reasons*. First, Castro county falls under the High Plains Underground Groundwater Conservation District #1 and recent studies have included the county as among those affected by groundwater pollution. Second, the increasing problem of groundwater depletion in other counties of the Conservation district may shift production of irrigated crops more to counties in the north including Castro. This brings the issue of nitrate pollution of the Ogallala directly to the forefront since more irrigation may entail the use of more fertilizers leading to higher levels of nitrate accumulation in the water.

The motivation for this study comes from the economic tradeoffs involved in agricultural production using irrigation water and nitrogen fertilizer as inputs against the attendant costs of groundwater pollution that may have serious consequences in the long run. Traces of nitrate content above the EPA safe limit were reported by Hudak (2000) in rural Castro County, the source of which is either animal feedlot operations or agricultural runoff. The objective in this research is to assess the importance of the latter as a source of nitrates in the groundwater. In particular, the goal is to address how the dynamic evolution of the nitrate stock is affected by the use of water for irrigation and nitrogen fertilizer applications. Simulated data generated by CRopman (a crop simulation model developed by Gerrick et al., 2003) is used to derive response functions and nitrogen leaching equations for four major types of crops grown viz. corn, cotton and grain sorghum. Next, the estimates for the response functions and the percolation equations

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[1] More than 80% of irrigated wells in Terry and Lynn Counties show nitrate concentration that exceeds the EPA MCL of 10mg/l.

are used to develop 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. Finally, 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 a constraint is imposed on the use of nitrogen fertilizer per acre, and second the price of nitrogen fertilizer is raised successively by 5% and 10%. Findings point towards a favorable impact on groundwater quality whenever the practice of restricting the use of the polluting input is implemented. In addition, policies aimed at raising the volume of water in storage like restricting the use of irrigation water use by around 0.50 acre-inches per acre from the average base value as well as buying out water rights also show positive results in terms of water quantity and quality.

2. Previous Studies

Groundwater management becomes more complex when the deteriorating quality of the water is a problem alongside the declining water level. Anderson, Opaluch, and Sullivan (1985) provide an early attempt at empirically modeling the relationship between pesticide application on the surface and its role as a groundwater pollutant. 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 estimated contamination function for the pesticide). Kim, Hostetler, and Amacher (1993)[2] and Conrad and Olson (1992) develop a water quality model where the behavior of the stock pollutant is depicted with a delayed response to the initial application of fertilizer and aldicarb. In two successive papers, Roseta-Palma (2002, 2003)

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[2] Their seminal contribution to groundwater delayed response was 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.

shows that both quantity and quality management is essential from an optimal point of view; otherwise, a steady-state solution would be equivalent to a myopic or competitive solution where agents are either taxed for 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 stresses a joint management strategy that relies on economic instruments such as taxes and/or quantitative restrictions to achieve a socially optimal solution for water withdrawal and pollution.

More recently, several agricultural economists developed case studies on this aspect of pollution. Notable among them are Fleming, Adams, and Kim (1995); Yadav (1997); and Nkonya and Featherstone (2000). Yadav (1997) and Nkoyna and Featherstone (2000) both look 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 came to the conclusion that residual nitrogen in the soil does affect the optimal rate of nitrogen application, Nkoyna and Featherstone conducted simulations on various parameters affecting the flow of nitrogen as a pollutant in groundwater and called for regulation standards or knowledge dissemination among farmers as possible management options. However, the delayed responses recognized in this research focus on the time lag for the percolation of nutrients and pesticides from the vadose zone to the aquifer; they do not incorporate the transport of the nutrients in 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 combines hydrological parameters with the amount of nitrogen leached to obtain a concentration of nitrate in groundwater. Based on this concentration they varied economic parameters under three different production functions to calculate optimal tax rates and resultant fall in nitrogen fertilizer application. They also find an important role of the time lag in nitrogen percolation. In another paper, Fleming and Adams (1997) look 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 of Malheur County, Oregon.

This study differs from past studies done on the Ogallala aquifer in Texas. First, it will look at the problems of nitrate pollution and groundwater extraction simultaneously. Recent research in Texas focuses on ways to conserve groundwater and prevent nitrate pollution problems as two independent areas of importance. No economic study to date focuses 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 any part of West Texas. Studies by Zeitouni and Dinar (1997); Dinar and Xepapadeas (1998); Hellegers, Zilberman, and Ireland (2006) focused on California, while Lacewell and Chowdhury (1993) looked at the pollution problem in the Edwards aquifer region in Texas. Finally, policy scenarios are developed for the joint management of the water stock and the pollutant to arrive at economically feasible solutions for groundwater extraction and pollution.

It is to be noted that the results shown here are based on irrigated agriculture for Castro County. Dryland or non-irrigated farming is not considered here. The main contribution of this study is to identify the economic impact of crop production using irrigation water from the Ogallala and nitrogen fertilizer as the two primary inputs and at the same time investigate the extent to which this production affects the water stock and quality level. It attempts to define policies for the economic use of these two resources which are likely to improve the present situation.

3. Theoretical Model

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. 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:

$$Max \sum_{t=0}^{T-1} [\beta^t \sum_{k=1}^{K} \{P_{kt} f_{kt}(x_{kt}, m_{kt}) - P_{mt} m_{kt}\} - C_t(X_t) x_t] \tag{3.1}$$

subject to:

$$X_{(t+1)} = X_t + \left[(1-\alpha) \sum_{k=1}^{K} x_{kt} - R \right] / AS \tag{3.2}$$

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

$$ST_{(t+1)} = ST_t - \left[(1-\alpha) \sum_{k=1}^{K} x_{kt} - R \right] / AS \tag{3.3}$$

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

$$M_{(t+1)} = \eta l_t + \ (1-\delta) M_t \tag{3.4}$$

$$\sum_{k=1}^{K} x_{kt} \leq \ GPC_t(X_t) \tag{3.5}$$

The model objective function is given by equation (3.1) 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 (3.1) represents the total cost of nitrogen fertilizer used for all crops produced over the decision-making horizon.

The last term in equation (3.1) 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 (3.2) – (3.5). 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, Willis, and Johnson (2010) and Wheeler (2008). (Also see Gisser (1983), and Gisser and Sanchez (1980)). Equation (3.2) represents the change in the pumping lift of the aquifer where X_t is the pumping lift of the aquifer at time *t*, α ($0 < \alpha < 1$) is the constant fraction of irrigation water applied in each period that is 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 (3.3). The remaining parameters are as previously defined in equation (3.2).

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 (3.4) 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 $l_t(x_t, m_t; g)$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 g 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 last component of the base model constraint, equation (3.5), 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.

4. Empirical Methodology

In the absence of actual data on irrigation and fertilizer use per acre and the amount of fertilizer being percolated, the study utilizes simulated data obtained from CRopman (Gerrick et al., 2003) to estimate crop response functions and nitrogen leaching equations. The crop prices correspond to a five-year average of FAPRI (Agricultural and Food Policy Center, Texas A&M University) prices, while the price of nitrogen fertilizer is taken from the Texas Crop Enterprise Budget for 2011 (Texas A&M University). The hydrologic parameters such as specific yield and the saturated thickness for the aquifer are taken from 2008 estimates published by the Center for

Geospatial Technology at Texas Tech University, while the economic parameters such as the pump efficiency, energy price, and the operating pressure of the pumping system are borrowed from the figures in Wheeler (2008).

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

$$C_t(X_t) = \frac{EF * (X_t + 2.31 * PSI) * EP}{EFF} \tag{4.1}$$

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 Das et al. (2010) and Wheeler (2008).

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[3]; each simulation is conducted for a 40-year period. 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).[4] 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. The final outputs are compiled taking into account the variables – irrigation 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

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[3] Vadose zone refers to the region of aeration above the water table.

[4] Due to lack of actual weather data, the program uses the monthly average values to generate weather data. Dimmitt, Texas is taken as the weather station for Castro.

nitrogen fertilizer applied for generating crop response functions, assuming different technological relationships between nitrogen and water. Leaching functions are estimated with mineral nitrogen loss with 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.

$$Y_i = \alpha_i \beta_i IR + \gamma_i N + \varepsilon_i \tag{4.2}$$

$$Y_i = \alpha_i + \beta_i IR + \gamma_i N + \delta_i IR^2 + \pi_i N^2 + \rho_i \, IR * N + \varepsilon_i \tag{4.3}$$

$$Y_i = \alpha_i + \beta_i IR + \gamma_i N + \delta_i IR^{1/2} + \pi_i N^{1/2} + \rho_i \, (IR * N)^{1/2} + \varepsilon_i \tag{4.4}$$

$$Y_i = \alpha_i + \beta_i IR * N + \gamma_i \, (IR * N)^2 + \varepsilon_i \tag{4.5}$$

where Y_i refers to the output of the *i*th 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 – 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 the high correlation with the dependent variable as evident from crop and county-specific simulated data. 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 (4.6)-(4.8), describe the technical relationships between leaching of mineral nitrogen as the dependent variable and the main independent variables.

$$NL_i = \alpha_i + \beta_i PRK + \vartheta_i GYLD + \gamma_i TNO3 + \delta_i IR + \pi_i N + \varepsilon_i \tag{4.6}$$

$$NL_i = \alpha_i + \beta_i PRK + \tau_i PREC + \gamma_i GYLD + \delta_i TNO3 + \pi_i IR + \rho_i N + \varepsilon_i \tag{4.7}$$

$$NL_i = \exp(\alpha_i + \beta_i GYLD + \gamma_i PRK + \delta_i TNO3 + \pi_i IR + \rho_i N + \tau_i(IR * N) + \varphi_i(IR * TNO3+\varepsilon i \tag{4.8}$$

Equations (4.6) and (4.7) are 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, *PREC* refers to the growing season precipitation, *TN*03 denotes the nitrogen associated with the soil, and *IR* and *N* are as defined above. Equation (4.8) is a nonlinear version that 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.[5]

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[5] The nonlinear leaching estimates did not converge for all crops when tried in SAS and hence the estimates are not reported here.

Table 1: Estimated coefficients for the yield functions for crops based on simulated data

	Corn	Sorghum	Cotton	Wheat
IR	15.99			
IR^2	-0.38			
N	0.48			
N^2	-0.00			
$IR^{½}$				
$N^{½}$				
$(IR * N)^{½}$				
IR * N	0.02	0.045^{***}	0.79^{*}	0.006
$(IR * N)^2$		-0.00000642^{**}	-0.0002	-0.0000025
Constant	-120.78	28.94^{**}	530.68	13.22

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

Table 2: Estimated coefficients for the leaching functions for crops based on simulated data

	Corn	Sorghum	Cotton	Wheat
PRK	0.200^{***}	0.23^{***}	31.18^{***}	1.76^{***}
CRF	0.009	1.03^{***}	-5.77^{***}	-4.92^{***}
GYLD	-0.007	-0.26^{***}	0.12^{***}	-2.27^{***}
TNO3	-0.004	-0.89^{***}	-0.06^{**}	-0.22^{***}
IR	-0.029	0.23^{**}	-17.28^{***}	-13.62^{***}
N	0.011	0.71^{**}	2.09^{***}	1.29^{***}
IR * N				
IR * TNO3				
Constant	-0.32	-11.09	1.91	47.47

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

The estimates for the response functions and the percolation equations (provided in Table1 and Table 2) 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. The method used to calculate the initial nitrate concentration in the aquifer is described in the appendix.

The base form of the optimization model aims to maximize the net present value (NPV) of crop production as given by equation (3.1) over a 20-year planning horizon subject to the constraint set formed by equations (3.2) – (3.5). The dynamic optimization modeling in short, serves to maximize the discounted net revenues over a 20 year planning horizon subject to certain economic and hydrologic constraints. For example, the Oklahoma Groundwater Law (1972) states that 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 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 NPV of production using a discount rate of 5% as commonly used in water quality studies.[6] Then we resolve the model 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 future. (In the pollution literature, this is referred to as a best management practice). As a contrast to this endogenously solved "tax rate," the price of nitrogen fertilizer is successively raised to \$0.52/lb (5% increase) and \$0.55/lb (10% increase). This may be thought of as an external tax on the fertilizer use. Finally a set of policies are implemented that restricts the use of water per acre along with restriction on the use of fertilizer. These are respectively a quota on the use of irrigation water per acre; a restriction on the terminal value for saturated thickness, which is allowed to drop to only 50 feet from the initial value of 79 feet; and a water rights buyout policy where an agent can sell water rights over the time period under

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

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 20-year period. On the other hand, the buyout policy offers a financial incentive on the agent to conserve water in the present period by selling water rights to groundwater over the 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 around 2 acre-inches of water less than the unrestricted base value. The purchase of water rights may take place through negotiations between agents and the High Plains Underground Water Conservation District (HPUWCD). This is similar to the USDA's Conservation Reserve Program and was followed in Wheeler (2008) for nine counties in Texas overlying the Ogallala aquifer. 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.[7]

5. Results

First we consider the solution from the unconstrained (base) optimization model. (Results appear in Table B1 in the appendix). Total irrigation water used per acre declines by around 0.22% at the end of Year 20 as the saturated thickness of the aquifer in the county is observed to fall from 79 feet at the start of the initial period to 44 feet. The base results demonstrate that due to the steady increase in the level of nitrogen percolation below the surface from 92.57 lb/acre to 94.02 lb/acre as a result of the unconstrained use of fertilizer per acre, the nitrate concentration picks

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[7] 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.

up in the later years to more than 17mg/l, much above the EPA maximum concentration limit for drinking water standard.

The next two policies describe the effect of an increase in the price of the fertilizer. With a 5% rise in fertilizer price (Table B.2), the discounted net revenue per acre falls by $4.57 from the base value in year 20, and the nitrate concentration in groundwater goes up to 16.27 mg/l at the end of Year 20, which is just 0.79 mg/l short of the corresponding base value. A possible reason might be the drop in the amount of fertilizer percolating beneath the surface to 89.43 lbs/acre by Year 20. 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 (refer to Table B.3) there is a fall in the level of nitrates in groundwater to 15.78 mg/l and the loss in NPV 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 156.70-157.22 lbs/acre while for a 10% rise, the application per acre ranges between 155.58 lbs-156.08 lbs. The base use of fertilizer on irrigated land is between 158.52 lbs/acre to 159.05 lbs/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, it may be inferred from the above discussions that a $0.03 tax on every pound of nitrogen applied is almost as effective in maintaining the groundwater quantity and quality as a $0.05 tax.

As an alternative to a direct increase in fertilizer prices, we devise a kind of “best management” scenario where the fertilizer use per acre is restricted to a certain limit. The economically feasible limit is selected to be in the range of 144-146 lb/acre of nitrogen applied by running several sensitivity tests to the base application level. Beyond 146 lbs/acre, the concentration of nitrate and the percolation of nitrogen below the root zone increases consistently. On the other hand, a restriction on nitrogen applied to below 144 lb/acre has a strong negative impact on the net revenues every year. Attention is restricted here to a fertilizer application level of 144 lbs/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 10 mg/l. The results are shown in Table B.4 in the appendix. The nitrate level is seen to fall to 10.36 mg/l and the percolation below the root zone falls drastically from 94.02 lbs/acre in the base run to 54.97 lbs/acre, which is a 40% decrease over the entire time period. The total cost incurred per acre is the lowest for this scenario even compared to the base case, with a difference of $3.88 at the end of the period from the base-year value. From a revenue perspective, the imposition of this constraint has two implications—one, the net present value differs slightly from the base level ($2.67 per acre loss in discounted revenue at Year 20), and secondly, the shadow prices that 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 144 lbs/ace.

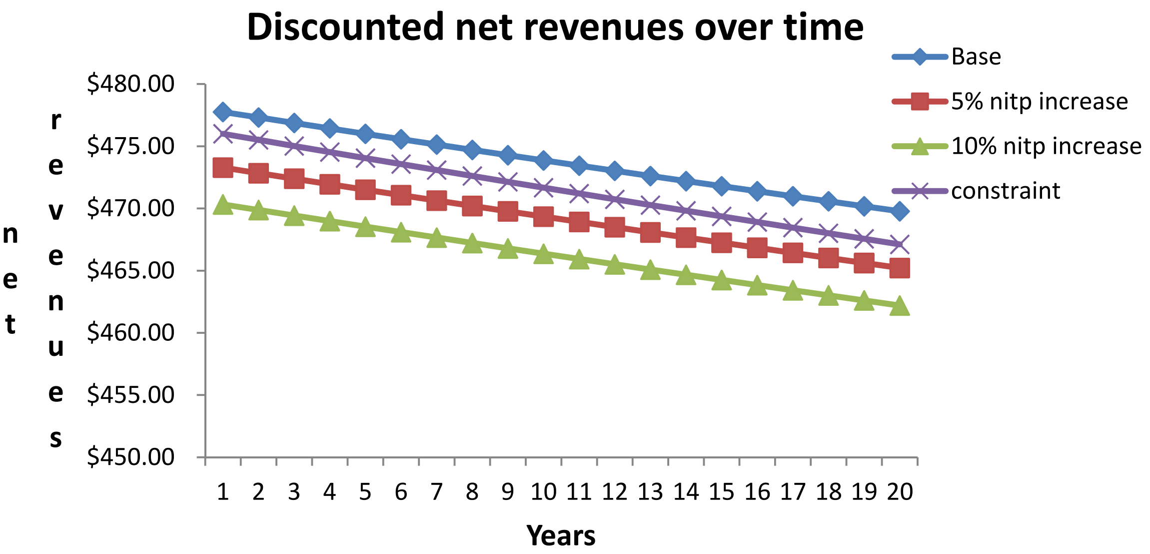

Fig. 1: The time path of discounted net revenues in the twenty year period for the base run and the three different policies

The above figure demonstrates the dynamic path of net revenues for the base case and the different policies. The discounted revenues differ by \$1-\$2 every year for the base run and with the constraint on fertilizer applied to 144 lbs/acre. The dynamic fall in the discounted revenues is due to the absence of any specific water conservation policy here, but it shows that the constrained optimization is closer to the base values in terms of net revenues over the planning horizon. The fall in discounted net revenues from the base run over the 20-year period is highest (\$7.43) for a 10% increase in the price of fertilizer or a tax of \$0.05 on the fertilizer use.

The figure below depicts the time path of the nitrate concentration in groundwater. Starting from the initial value of 6.37 mg/l, the concentration levels are not affected to a large extent by an increase in fertilizer price to 5% and 10%, decreasing by 5% and 8%, respectively, from base year values at the end of Year 20. When the use of fertilizer is restricted to 144 lbs/acre, there is a fall in nitrate levels by 39% at the end of the planning horizon.

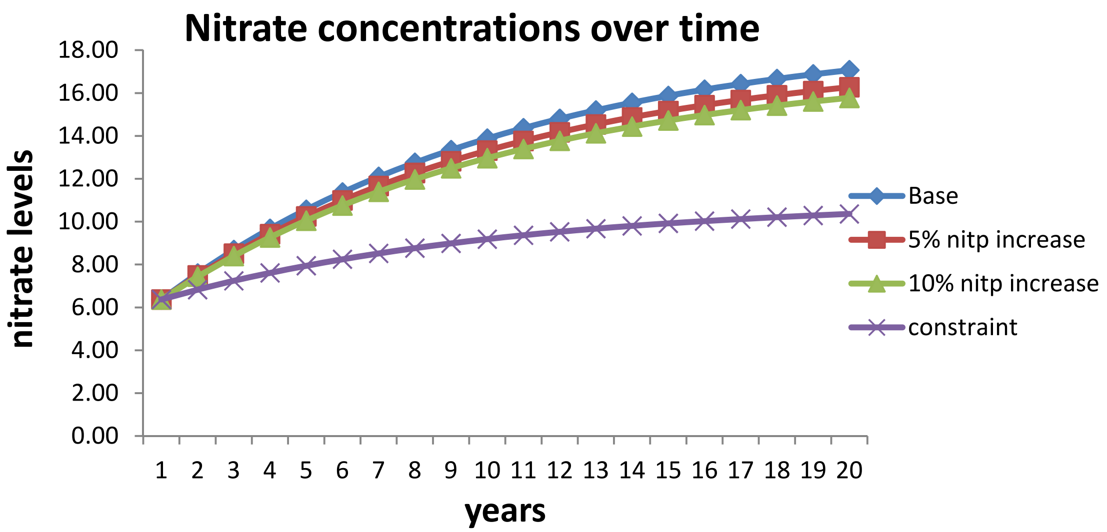

Fig.2: The time path of the nitrate concentration in groundwater for the base run and the three different policies

Economic policy instruments to conserve the stock of water as well as controlling the stock of pollutant are considered next. The quota policy (the results are shown in Table B.5 in the appendix) restricts the amount of irrigation water use by 0.50 acre-inches 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 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 20. There is a loss in net present value of $241.34 per acre, which follows from a fall in net revenues since the total cost, including the cost of water withdrawal, falls by around 9% in Year 20 due to the restriction.

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. Table B.6 in the appendix illustrates the results. 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 which is 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 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 197,264.7 acre feet of water conserved in terms of projected irrigated acres of land over the entire time period.

The final policy is to evaluate the impact of a 20-year water rights buyout along with restriction on the use of nitrogen fertilizer for Castro County. (refer to Table B.7 in the appendix). 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. This has a direct bearing upon the pumping cost, which reduces to \$4.66/acre-inch on average over the 20 years. The notable effects are on the discounted net revenues and the level of nitrate in the water. The latter increases by only 4 mg/l over the twenty years. The agents also reap the maximum financial benefit from the buyout policy with a net gain in NPV of production of \$209.82/acre from the base level.

Table 3: Change in discounted net revenues per acre over the 20-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. *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 between $14.07 to $17.21 per acre 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 4 and Figs. 3 and 4 below show the effect on saturated thickness and nitrate concentration over the 20-year time period. Evidently, the fall in saturated thickness over time is lowest for the buyout policy, while the dynamic time paths for the saturated thickness differ very little between the base level and on imposition of the quota on water use.

Table 4: Change in saturated thickness over the 20 years for the base situation and the different policies

Years	Base	quota	satt_50	buyout
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	75.89
4	73.28	73.63	73.97	74.35
5	71.39	71.86	72.31	72.82
6	69.51	70.10	70.66	71.29
7	67.64	68.3	69.02	69.78
8	65.78	66.60	67.39	68.27
9	63.94	64.87	65.76	66.77
10	62.09	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	56.36	57.88	59.47
15	53.11	54.70	56.42	57.98
16	51.35	53.05	55.02	56.55
17	49.59	51.40	53.67	55.12
18	47.84	49.75	52.38	53.69
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.

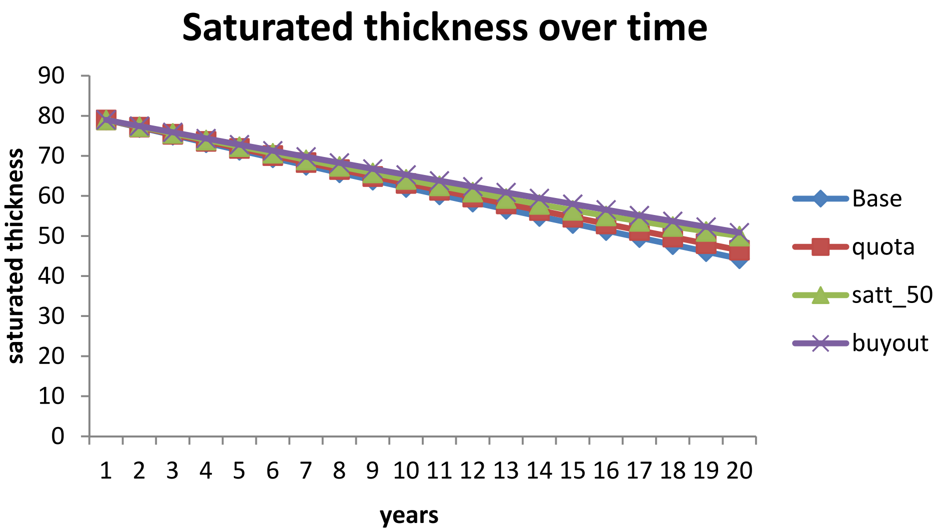

Fig.3: The time path of saturated thickness of the aquifer in the twenty year period for the base run and the water management policies

As far as the contribution to the pollutant stock is concerned, the buyout policy also has the least impact as is shown in Fig. 4. As the figure shows, the policy of putting a constraint on the use of fertilizer alone has a similar impact upon the accumulation of nitrate stock over time.

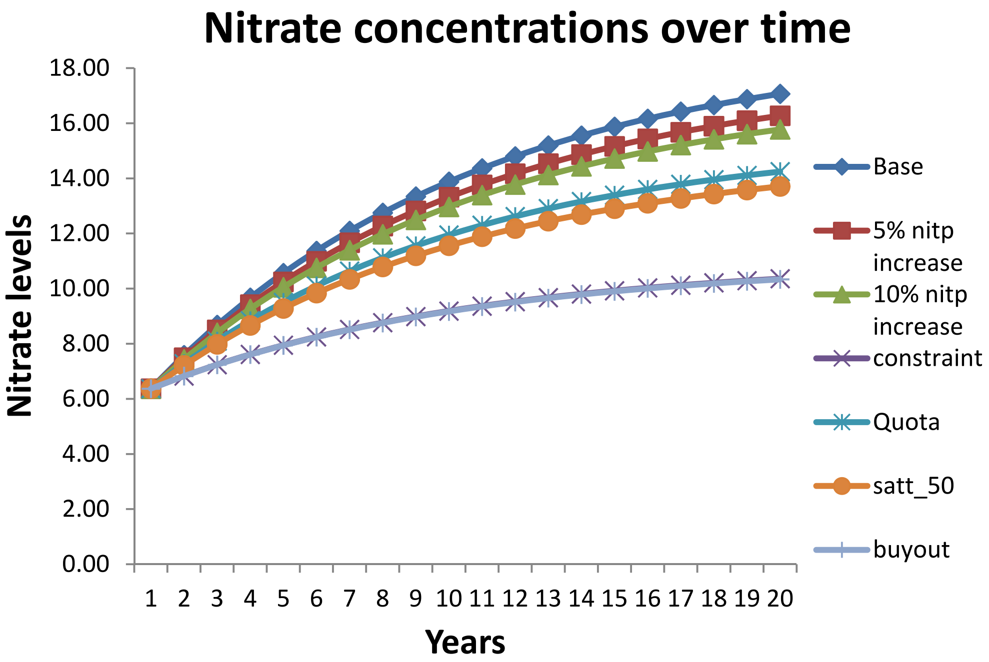

Fig.4: The time path of the nitrate level in the aquifer in the twenty year period for the base run and the different policies

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 20 to a mere 5% from the base value. However, the fall in NPV per acre to much above \$50[8] 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, regulator but is a direct disincentive to agents. 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, there is the difficulty in calculating the actual tax rate over the years when the fertilizer constraint is binding.

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[8] The net present value per acre is \$6,517 for the base run while it amounts to \$6,455.62 per acre for a 5% increase in fertilizer price per pound and to \$6,414.68 per acre for a 10% increase.

If the use of fertilizer is strictly monitored and is found to exceed the stipulated level in any particular year, then an average tax rate based on the shadow prices can be computed and imposed on the use per pound of nitrogen.[9] 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; the penalty as reflected in these shadow prices may not turn out to be sufficiently high to compel the agent to restrict 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

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[9] The shadow prices range from $0.34-$0.14/lb. of excess fertilizer applied for the entire period. When an average of these prices was added to the actual price of nitrogen and the model solved with that price (approx. $0.72/lb), then the net revenues were affected but there was a positive impact on the water quality.

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 in the water level of 34 feet. So from policy perspective, this stands out as most effective as far the solutions from the optimization models are concerned.[10]

Three features stand out in favor of a buyout policy. First, by purchasing water rights from the irrigator the regulatory agency ensures that the stock of water does not get exhausted in the near future. Second, it does not directly impose a pumping restriction on the user for maintaining the stock of water unlike the other two policies. Finally, such an arrangement ensures that the conservation incentives fall on the agent herself. However, it should be remembered that all these policies are accompanied by the administrative costs of metering wells and monitoring which may be accepted as regular environmental transaction costs. Seldom are these costs prohibitively high for the regulatory body (the HPUWCD) aiming for long term water conservation goals.

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 after weighing the costs and benefits of each option. It should be noted that the results here for Castro County are not unique and can be replicated for policy recommendations for other regions of Texas with varying site specific parameters. Yet, the effectiveness of each of the above policies

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[10] For a complete illustration of the effect of the different policies on the net revenues and the pollutant stock refer to Tables B.8-B.9 in the appendix.

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.

6. Conclusions

The High Plains region in West Texas has been the focus of water conservation policies for the last two decades because of rapid depletion of groundwater in this region. Recently, attention has been drawn on nitrate pollution of the Ogallala aquifer, though no study or research report has come up with a joint management solution to cope with both of these problems. This research attempts to fill in this gap, taking the rural county of Castro as a case study. The main objective is 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 period. 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 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 might imply 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.

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 a constraint is imposed on the use of nitrogen fertilizer per acre and second, the price of nitrogen fertilizer is raised successively by 5% and 10%. In the absence of data on the geophysical transport of the input and its conversion into pollutant, a policy of curtailing the input use is a possible management strategy for controlling the pollution at the source of its application. This policy is effective as far as the impact on water quality and discounted net returns is concerned. However, the question remains on how to impose this tax on the agents considering that the shadow prices on the constraint set 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. 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. Allowing the irrigation water use not to exceed a certain limit and the saturated thickness not to fall below 50 feet are explored. Though these policies have positive impacts upon the stock of water and the stock of pollutant relative to the base situation, unfavorable impacts on the discounted net revenues leave them open to policy debate in terms of implementation. As far as the effect on discounted net revenues, stock of water conserved and the level of pollutant for Castro county are concerned, the water rights buyout option offers the best strategy for policy makers seeking a long term objective. The practice of purchasing water rights over a definite time period so as to provide users a direct incentive for conservation is not new but the depletable nature of groundwater in this region makes it a viable option. From a policy perspective, it contributes through the revenue side and thus adds to the strategy of only imposing a constraint on the polluting input.

We conclude with certain limitations of the above study. 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. 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, we could not incorporate it in the main modeling. 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. Finally, some explicit water conservation policies counteracting the rule of capture viz., a permit market may be introduced that may instill private property incentives in agents. Empirical assessment of such policies as instruments for groundwater management in West Texas is a direction for future research.

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Appendix

A1: 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 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 through location-based parameters like rows and columns with the help of Arc GIS. These are taken as location variables for the wells, while well depths and year of measurements are obtained from the TWDB well database. These wells are measured multiple times over the entire time period, while some wells are tested once or twice for the level of nitrate concentration. Thus, a cross sectional regression (see equation below) of concentration level on the main independent variables mentioned above is carried out using weighted least squares with well depths as weights.

$$M_t = \gamma_0 + \gamma_1 row + \gamma_2 col + \gamma_3 depth + \gamma_4 year + \varepsilon_t$$

Table B.1: Base run

Years	Irr ac-in/ acre	Fert lbs/acre	Percolation lbs/acre	Nitconc mg/liter	Satthickness feet	Plift feet	Pcost $/ac-inch	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* = 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 inch, *discounted NR* = discounted value of net revenues over the years from this activity.

NPV: $6517/acre

Table B.2: 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-inch	Discounted NR \$/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* = 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, *tcost* = total cost of crop production per acre, and *discounted NR* = discounted value of net revenues over the years from this activity.

NPV: \$6455.62/acre

Table B.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-inch	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* = 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:$6414.68/acre

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

Years	Irr ac-in/acre	Fert lbs/acre	Shadow Prices $/lb	Percolation lbs/acre	Nitconc mg/liter	Satthickness Feet	Plift Feet	Pcost $/ac-inch	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

Table B.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 ac-in/ acre	Fert lbs/acre	Percolation lbs/acre	Nitconc mg/liter	Satthickness feet	Plift feet	Pcost $/ac-inch	Discounted NR $/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* = 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: $6275.66/acre

Table B.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-inch	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* = 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: $5645.08/acre.

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

years	irr ac-in/acre	fert lbs/acre	percolation lbs/acre	nitconc mg/liter	satthickness feet	plift feet	pcost $/acinch	discounted NR $/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* = 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: $6726.82/acre

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

Years	Base $/acre	Nitp_0.52 $/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* = price of fertilizer being raised by 5% and 10%, respectively. *Constraint* refers to the restriction on fertilizer use by 144 lbs per acre *Quota* = restriction of irrigation water use by $0.50 per acre-inch from the average base value. S*att_50* = saturated thickness restricted to 50 feet at the end of the terminal period, while *buyout* = purchase of water rights by around 2 acre-inches per acre by the Groundwater Conservation District.

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

Years	Base mg/l	Nitp_0.52 mg/l	Nitp_0.55 mg/l	Constraint mg/l	Quota mg/l	Satt_50 mg/l	Buyout mg/l
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* = price of fertilizer being raised by 5% and 10%, respectively. *Constraint* refers to the restriction on fertilizer use by 144 lbs per acre *Quota* = restriction of irrigation water use by $0.50 per acre-inch from the average base value. S*att_50* = saturated thickness restricted to 50 feet at the end of the terminal period, while *buyout* = purchase of water rights by around 2 acre-inches per acre by the Groundwater Conservation District.