Evaluation of Water Conservation Policy Alternatives for the Southern High Plains of Texas

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Abstract

Three alternative groundwater conservation policies were examined for their impact on the regional economy of the Southern High Plains of Texas using nonlinear optimization models and an input-output model. Restriction of drawdown of the aquifer was found to be more effective than proposed water use fees.

Keywords: groundwater conservation, input-output model, nonlinear dynamic optimization, Ogallala Aquifer.

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Evaluation of Water Conservation Policy Alternatives for the Southern High Plains of Texas

The Southern High Plains of Texas is facing a future water shortage caused by the declining water levels of the Ogallala Aquifer. Municipal water availability is not considered to be in a crisis situation at the present time, but water available for agricultural irrigation is declining in some areas to the point of economic or physical depletion. As water available for irrigation declines, yields of agricultural products will decrease. The economic impact of decreased agricultural production and sales may impact rural communities negatively sooner than a municipal water availability crisis.

The source of irrigation water for this region is the southern portion of the Ogallala Aquifer. The Ogallala Aquifer is considered an exhaustible aquifer in this region due to a low recharge rate and pumpage far exceeding recharge. Agriculture uses 95% of the water pumped from the aquifer in the Southern Texas High Plains (HDR, 2001). Water use varies across the region due to water availability, measured by saturated thickness, and by cost of pumping, measured by depth to water or pumping lift. As the level of water available for irrigation decreases toward depletion, irrigators will convert from irrigated cropping practices to non-irrigated cropping practices or rangeland grazing. Because the saturated thickness and pumping rate vary throughout the region, the transition from irrigated land use will proceed at different rates across the region. Reductions in irrigated acreage will decrease yields and agricultural sales through time. The transition will have a gradual effect on the region, as well as on individual farmers. As saturated thickness decreases, the amount of water available at each well and the rate of pumpage will decrease, resulting in fewer acres irrigated per well. As the amount of water pumped decreases, crop production will decrease resulting in an increase in average fixed costs. Rather than an immediate transition from irrigated to dryland cropping practices, each irrigating farmer will irrigate fewer acres over time, contributing to the decrease in irrigated acres in the region. As the trend advances toward fewer irrigated acres, farms will become larger and the number of farmers in the region will decrease.

Reduced yields and revenue will adversely affect the economic base of many rural communities. With the transition to non-irrigated crop practices, agricultural crop production will decline. As sales of agricultural commodities and purchase of agricultural inputs decline, the amount of revenue flowing through a community's economy will decrease. Thus, an efficient management plan for aquifer water use should consider the impact of reductions in water availability on regional economic activity.

Specific Problem

Adoption and implementation of effective water conservation policies can extend the life of the Ogallala Aquifer in the Southern High Plains of Texas. With the passage of Texas Senate Bill 2 in 2002, Texas underground water conservation districts were given the authority to restrict a landowner's use of water and impose production fees (water use fees). If underground water conservation districts begin to implement policies that reduce pumpage, this could result in the extension of the life of the Ogallala Aquifer. By restricting the amount of water to be used for irrigation, individual farmers would plant fewer irrigated acres and more non-irrigated acres than with unrestricted water use, but they would be able to irrigate longer into the future on the reduced number of irrigated acres.

Objectives

The primary objective of this study was to analyze the impact of water conservation policy alternatives on the regional economy of the Southern High Plains of Texas. The specific objectives were to:

1. Estimate the economic life of the aquifer across the region under different water conservation scenarios;
2. Identify water conservation policy alternatives to extend the life of the aquifer; and
3. Evaluate the regional economic impact of the implementation of the various water conservation policy alternatives.

Methods and Procedures

General Approach

In order to analyze the impact of water conservation policy alternatives for the regional economy of the Southern High Plains of Texas, a two-step process was used. Dynamic optimization models were used to estimate the economic life of the aquifer for each county across the region under different water conservation scenarios. The results from the dynamic models were subsequently used in an input-output model to estimate the regional economic impact of the various water conservation scenarios.

Water Conservation Policy Alternatives

Bredehoeft and Young (1970) suggested three types of instruments that could be used in aquifer management: centralized decision-making, assigned quotas or pumping rights, and extraction fees or taxes on withdrawals. Bredehoeft and Young acknowledged that centralized decision making is unlikely to be adopted because it runs counter to traditional management policies. The other instruments of quota and fees are possible and within the authority of groundwater conservation districts in Texas.

Model Development

The overall study region includes the 19 counties of the Southern High Plains of Texas within the Groundwater Management Area 2 (GMA2). The general model used in this study was a modification of the models used by Feng (1992) and Terrell (1998) with adjustments made to develop a nonlinear dynamic model that incorporated nonlinear crop enterprise production functions. The model used recharge data developed by Stovall (2001) in his groundwater hydrology model that assessed the groundwater resources of the Southern High Plains of Texas.

The models developed for this study estimated the optimal level of water extraction for irrigation and the resulting net present value of net returns over a planning horizon of 50 years. The models were run for a baseline scenario with no change in water conservation policy and for three conservation policy alternatives: (1) a production fee of $1 per acre-foot pumped, (2) an annual restriction of water use to 75% of a 10 year average water use, and (3) a restriction on the drawdown of the aquifer over the 50-year planning horizon to 50% of the initial saturated thickness at the beginning of the period. The results of the nonlinear dynamic model were used in the input-output model to determine the impact of the three water conservation policy alternatives on the regional economy.

Dynamic Non-linear Programming Model

Rowse (1995) demonstrates the adaptability of integrated algebraic modeling and optimization software packages such as GAMS and illustrates the effectiveness of using a single computing environment with these software packages. Non-linear dynamic programming with

GAMS was used in this study to facilitate multiple runs of the model considering different water conservation scenarios.

In order to develop the non-linear programming model, the functional relationship between yield and applied irrigation water was estimated using the Crop Production and Management Model (CROPMAN) (Gerik and Harman, 2003). The CROPMAN model was used to develop the production functions describing the yield response to applied water. The model requires the user to designate the crop, type of irrigation system, soil type, and weather station location. The gross soil type was selected using the USDA soil map for each county and selecting the predominant soil type shown for the major crop producing region of the county (USDA, various counties).

The production functions for irrigated crops were estimated for corn, cotton, grain sorghum, peanuts, and wheat. The production techniques and timing of cultural practices were held constant with only the irrigation amounts varying. The irrigation timing was also held constant with the amount of irrigation water applied divided between the various dates of irrigation. The yields were recorded for each irrigation amount for each crop.

Yield response functions were estimated using a quadratic functional form with yield per acre as the dependent variable and irrigated water applied as the independent variable. The quadratic form was used to ensure a global maximum would be achieved in the optimization model. The models were estimated using the ordinary least squares regression technique.

Dryland yields were calculated in a similar fashion, using the same soil type and weather stations, but different production techniques, thereby, incorporating the different management techniques required for dryland crop production.

The optimization model incorporated the production functions estimated from CROPMAN to develop a non-linear form of the model which was solved using GAMS (Brooke, et al, 1998). An optimization model was developed for each of the counties in the study area. County specific data for each model included land area of the county, land area of the county overlying the Ogallala Aquifer, amount of annual recharge, specific yield for the aquifer, initial saturated thickness, initial pumping lift, initial well yield, initial acres per well, initial acres per crop, and initial number of irrigated acres in the county.

Crop specific data include the 15-year average of commodity prices, variable costs of dryland crop production excluding harvest costs, the added variable costs for irrigated crop production, and harvest costs per unit of production. Commodity prices used in the analysis are averages of monthly prices for fifteen years as reported by the Texas Agricultural Statistics Service (various years). The variable costs for dryland crop production, the additional costs for irrigation, and harvest costs per unit of production were also taken from the Texas Cooperative Extension Service Budgets for District 2.

Irrigation energy costs were calculated using a factor for electricity of 0.164 KWH / feet of lift / acre-inch, irrigation system operating pressure of 16.5 pounds per square inch, electricity price of $0.0633 per KWH, and pump engine efficiency of 50%. Other costs include the initial cost of the irrigation system of $280 per acre, annual depreciation percentage of 5%, irrigation labor of 2 hours per acre, labor cost of $8 per hour, annual maintenance cost of 8% of initial cost, and a discount rate of 3%. Cost calculations included harvest costs, pumping costs, and total costs of production for irrigated and dryland crops. The units for the resulting values are dollars per acre ($/acre).

Specification of the dynamic non-linear optimization model.

The objective function of the optimization model maximized the net present value of annual net returns to land, management, groundwater stock, risk, and investment. Annual net income may be expressed as:

$$(1) \qquad NI_t = \sum_c \sum_i \Theta_{cit} \{(P_c Y_{cit}) - C_{cit}(WP_{cit}, L_t, ST_t)\},$$

where *c* represents the crop grown, *i* represents the type of irrigation system, and *t* represents the time period, Θ_{cit} represents the percentage of crop *c* produced by irrigation system *i* in period *t,* P_c represents the price of crop *c*, Y_{cit} represents the yield per acre of crop *c* produced by irrigation system *i* in period *t*, C_{cit} represents the cost of production per acre of crop *c* produced by irrigation system *i* in period *t*, WP_{cit} represents the acre-feet of water applied per acre to crop *c* produced by irrigation system *i* in period *t*, L_t represents the pumping lift in feet in time *t*, ST_t represents the saturated thickness of the aquifer in time *t,* and NI_t represents the net income in time *t*. Yield (Y_{cit}) is calculated using the production functions derived from the CROPMAN model as previously discussed. The objective function was maximized for a 50-year planning horizon and may be expressed as:

$$(2) \qquad Maximize NPVR = \sum_{t=1}^{50} NI_t (1+r)^{-t},$$

where NPVR is the net present value of net income and *r* represents the social discount rate of 3%.

The dynamic optimization model can be represented as:

$$(3) \qquad Maximize NPVR = \sum_c \sum_i \sum_t \Theta_{cit} \{(P_c Y_{cit}) - C_{cit}(WP_{cit}, L_t, ST_t)\}(1+r)^{-t};$$

Subject to:

(4) $$ST_{t+1} = ST_t - \left[\left(\sum_c \sum_i \Theta_{cit} WP_{cit} \right) - R_t \right] A/s;$$

(5) $$L_{t+1} = L_t - \left[\left(\sum_c \sum_i \Theta_{cit} WP_{cit} \right) - R_t \right] A/s;$$

(6) $$GPC_t = (ST_t / IST)^2 * (4.42 * WY / AW);$$

(7) $$WT_t = \sum_c \sum_i \Theta_{cit} * WP_{cit};$$

(8) $$WT_t \le GPC_t;$$

(9) $$PC_{cit} = \{[EF(L_t + 2.31 * PSI)EP] / EFF\} * WP_{cit};$$

(10) $$C_{cit} = VC_{ci} + PC_{cit} + HC_{cit} + MC_i + DP_i + LC_i;$$

(11) $$\sum_c \sum_i \Theta_{ci} \le 1 \text{ for all } t \ ;$$

(12) $$\Theta_{cit} \ge 0.9 \Theta_{cit-1}; \text{ and}$$

(13) $$\Theta_{cit} \ge 0.$$

The objective function in Equation 3 was obtained by substituting Equation 1 into Equation 2. Equations 4 and 5 are equations of motion for the two state variables of saturated thickness (ST_t) and pumping lift (L_t), where R_t is the annual recharge rate in feet, A is the percentage of irrigated acres expressed as the initial number of irrigated acres in the county divided by the area of the county overlying the aquifer, s represents the specific yield of the aquifer.

Equations 6, 7, and 8 express the relationship between the amount of water used and the amount of water available. Equation 6 expresses the amount of water available to be pumped as gross pumping capacity (GPC_t) in period t, where IST is the initial saturated thickness (Harman, 1966), WY is the average initial well yield for the county, AW is the average number of wells per irrigated acre for the county (Terrell, 1998), and 4.42 acre-inches per gallon per minute (acin/gpm) is a factor developed from the assumption of 2000 pumping hours in a growing season. From the assumption of 2000 pumping hours, the following relationship was developed :

> (2000 hours) * (60 minutes / hour) * (43560 cubic feet / acre-foot) / (7.48 gallons / cubic foot) * (12 inches / foot) = 4.42 acre-inches / gallon per minute.

Equation 7 expresses the total amount of water pumped per acre (WT_t) as the sum of water pumped on each crop. Equation 8 is the constraint requiring the amount of water pumped (WT_t) to be less than or equal to the amount of water available for pumping (GPC_t).

Equations 9 and 10 are cost functions. Equation 9 expresses the cost of pumping (PC_{cit}) for crop c produced by irrigation system i in period t, where EF represents the energy use factor for electricity, PSI represents the irrigation system operating pressure, EP represents energy price for electricity, EFF represents pump engine efficiency, and the factor 2.31 feet is the height of a column of water that will exert a pressure of 1 pound per square inch (Terrell, 1998). Equation 10 expresses the cost of production (C_{cit}) for crop c produced by irrigation system i in period t, where VC_{ci} is the variable cost of production per acre, HC_{cit} is the harvest costs per acre, MC_i is the maintenance cost per acre for the irrigation system, DP_i is the depreciation cost per acre for the irrigation system, and LC_i is the irrigation labor cost per acre for the irrigation system.

Equation 11 limits the sum of acres for all crops c produced by all irrigation systems i for each period t to be less than or equal to 1. Equation 12 limits the annual shift from any crop to 90% of the previous year's acreage. This limit on the rate of transition between crop enterprises attempts to control the rate at which the model switches from one enterprise to another in order to replicate an orderly transition between crop enterprises. Equation 13 ensures that the values of the decision variables are non-negative.

Input-Output Model

The next step after obtaining the dynamic nonlinear optimization solutions was to use the results of the analysis in the input-output model, IMPLAN, to estimate the regional economic impact of each of the three water policy alternatives as compared to the baseline scenario (Minnesota IMPLAN Group, Inc., 2000). The economic activity of the production of corn, cotton, grain sorghum, peanuts, and winter wheat under the three water policy scenarios was analyzed in 10-year increments that resulted in five "snapshots" for years 10, 20, 30, 40, and 50 of the planning horizon (Terrell, Johnson, and Segarra, 2002). The activity entered into IMPLAN's impact analysis program was the change in gross revenue from the baseline scenario for each of the commodities as a result of the change in water policy.

The IMPLAN model was developed for the 19-county study region using the 1998 dataset. The descriptive model was first developed for the baseline scenario using the 19-county region, then the predictive model was developed using the Type SAM multipliers that consider direct, indirect, and induced effects. The impact analysis used the net income for each crop in the designated years and input into their respective economic sectors of cotton for the change in gross revenue from the baseline scenario for cotton; feed grains for the change in gross revenue from the baseline scenario for corn, grain sorghum, and winter wheat; and miscellaneous crops for the change in gross revenue from the baseline scenario for peanuts.

Results

The primary objective of this study was to analyze the impact of water conservation policy alternatives on the regional economy of the Southern High Plains of Texas. This section describes the results of the non-linear optimization model under the baseline scenario and three water conservation scenarios and the results of the input-output model showing the regional economic impacts of the water conservation policy alternatives.

A baseline scenario was developed that provided a set of values for water use per acre, saturated thickness, pumping lift, gross revenue per acre, and net income per acre. This baseline scenario assumed no new water policies to be imposed over the 50-year planning horizon. The results were used as a set of values by which to compare the impact of the three alternative water policies. The models for each alternative scenario provided values resulting from single changes in the model reflecting the described scenario. The results of this study considered the changes in water use per acre, saturated thickness, pumping lift, gross revenue per acre, net income per acre, and economic impact for the region as the differences of the values of the alternative policy scenarios from the values found in the baseline scenario. The focus of the analysis of this study was on the differences between the values from the alternative scenarios and the baseline values as indicators of the impact of the water polices rather than a focus on the absolute values of the results of the scenarios.

The alternative scenario that imposed production fees of $1 per acre-foot exhibited little change from the baseline scenario. Irrigated acres changed less than 1% throughout the period until year 45 when the difference increased to 3% below the baseline scenario by year 50. The change in water use increased beginning in year 3 and ended with 17% less water used annually in year 50 than in the baseline scenario. The saturated thickness in year 50 was 6.5% greater than the baseline scenario and the annual net income per acre in year 50 was 1.5% less than the baseline scenario.

The alternative water policy scenario that restricted annual water use resulted in an immediate decrease in water used and crop revenue. The level of annual water use stabilized in year 28 with the end result of a level of saturated thickness 30% greater that the baseline by the end of the 50-year period. The net present value of net income per acre, however, was dramatically lower than baseline and the lowest of the three alternatives considered, at approximately 15% below baseline.

The alternative water policy scenario that restricted the amount of drawdown of the aquifer to 50% of the initial level of saturated thickness resulted in a level of saturated thickness similar to the annual water use restriction alternative at the end of the 50-year period and a net present value of annual net income only 6% below baseline levels. This method allowed more producer flexibility than the annual water use restriction resulting in water use and cropping patterns similar to the baseline early in the period but progressing in a slower transition to a level of crop production that allowed more water being saved.

The difference in net present value of annual net income between these two methods of water pumpage restriction is a result of the discount rate and the time value of money. The annual water use restriction method caused an immediate decrease in water use and crop production in the early years of the period when the present value of annual net income was highest. The method restricting the aquifer drawdown allowed continued production and water use early in the period with restricting condition beginning during the latter half of the 50-year period when present value was lower than earlier years.

The effectiveness of the three methods can be measured with a ratio comparing the change in net present value of annual net income per acre from baseline and the associated change in level of saturated thickness. The values for the ratios are $11.58 per foot of saturated thickness change for the production fee scenario, $8.20 per foot of saturated thickness change for the annual restriction scenario, and $3.86 per foot of saturated thickness change for the drawdown restriction scenario. The method restricting aquifer drawdown is much more effective than the other alternatives considered. These values represent the cost in reduced net income per acre per foot of saturated thickness remaining above the baseline at the end of the 50-year planning horizon. The purpose of the ratio is to establish a cost of maintaining the water in the aquifer rather than pumping it. The negative change in the net present value of the annual net income, or loss, is considered the cost of maintaining the water for each scenario. The benefit for each scenario is the positive change in the level of saturated thickness of the aquifer. The ratio demonstrates the effectiveness of each scenario by showing the cost associated with maintaining one acre-foot of water in the aquifer rather than pumping.

The results of the economic impact analysis of the policy alternatives were very similar to the results of the net present value of net income analysis. The production fee scenario shows very little change from the baseline scenario with values less than 1% throughout the 50-year planning horizon. The annual values of economic output are less than $60 million below the baseline scenario through year 40 then an annual value of $237 million below the baseline scenario for year 50. The decrease in employment for the region shows similar percentages with values of less than 650 jobs below the baseline scenario through year 40 then a value of 2450 jobs below baseline for year 50.

The economic impact of the annual restriction of water use scenario showed an immediate decrease of almost $1.5 billion by year 10 below the baseline scenario, then an increase throughout the period to a value of $21 million above the baseline by year 50. Employment values were similar with a decrease in over 16,000 jobs below baseline by year 10 then an increase throughout the period to a value of almost 500 jobs over the baseline scenario by year 50.

The economic output of the scenario that restricted drawdown had values that decreased throughout the period to a low of $850 million below the baseline scenario by year 40. Employment values show a decrease on over 10,000 jobs below the baseline scenario by year 50.

Policy Implications

Of the three alternatives evaluated, the alternative that restricts drawdown to 50% of the initial saturated thickness is the most effective, saving the most water in the aquifer at the least cost to the regional economy. This policy has several advantages compared to the other policies evaluated. Agricultural producers would have more flexibility in managing their irrigation practices under this scenario compared to the restriction on annual water use. Producers would be able to increase irrigation in years with less rainfall and reduce irrigation in years with above average rainfall. An annual pumpage restriction could create a situation where producers would be unable to supply the optimal levels of irrigation water in drought years, whereas, the drawdown restriction provides the flexibility for producers to make those decisions in extreme situations such as drought.

The cost of administering the production fee and annual water use restriction policies would appear to be greater than a restriction on aquifer drawdown. The production fee and annual water use restriction alternatives would require the installation of metering devices to measure annual water withdrawal from each well. This would represent a significant cost across the region for meter installation and for personnel to read all meters on a regular basis. The restriction on drawdown could be measured using the present method of measuring wells that would not require the investment in metering the withdrawal from each well.

The production fee scenario did not cause as much reduction in the loss of saturated thickness relative to the annual water use restriction scenario or the restriction on drawdown of saturated thickness. The production fee authorized in Senate Bill 2 of $1 per acre-foot is not sufficient to impact an irrigator's decision with respect to the levels of water applied. A much higher production fee will be required for this type of policy to be effective in reducing irrigation levels.

Other considerations that are beyond the scope of this study are the cost of administering the different alternatives and the popular and political reception of the different alternatives. It seems that the drawdown restriction policy is the least intrusive to the water user and the most easily monitored, therefore, the most popular and least costly in addition to being the most effective.

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