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Effectiveness of Two Water Conservation Policies: An Integrated Modeling Approach

Biswa R. Das, David B. Willis, and Jeffrey Johnson

Agriculture in the Texas High Plains depends entirely on the Ogallala Aquifer. Texas enacted water conservation legislation to address declining reserves in the aquifer. We developed an integrated regional water policy model that links a hydrology model with an economic optimization model to estimate policy impacts with respect to economic cost and water conservation. Testing the effectiveness of two policies, a groundwater extraction tax and extraction quotas, we observe that neither significantly inhibits groundwater use. Although both policies conserve similar amounts of groundwater, the regional cost of the tax policy to agriculture is more than the quota policy.

Key Words: integrated regional water policy model, Texas High Plains, water conservation policy, hydrology model, economic optimization model, Ogallala Aquifer, tax policy, quota policy

JEL Classifications: Q30, Q31, Q38

Agriculture in the Texas High Plains (THP) depends entirely on the availability of groundwater in the Southern Ogallala[1] Aquifer (High Plains Underground Water Conservation District, 2004). Beginning in the 1940s and until the late 1970s, agricultural producers took advantage of Texas groundwater law, commonly referred to as the "right of capture," which granted landowners a complete property right to all groundwater reserves beneath a landowner's land (Kaiser and Skillern, 2001). A falling water table, which increased pump lifts, and the high energy prices in the late 1970s gradually reduced groundwater withdrawals and irrigated acreage. In 2002, 3.5 million THP crop acres were irrigated, approximately 55% less than the 8.1 million acres irrigated in the late 1960s (Texas Senate Bill 2, Austin, TX, 2002).

Texas legislation, specifically Senate Bills 1 (Texas Senate Bill 1, Austin, TX, 1997) and 2 (Texas Senate Bill 2, Austin, TX, 2002), explicitly recognized the growing scarcity of groundwater supplies. Senate Bill 1 (SB 1) fundamentally changed the structure of water management in the state by modifying several sections of the Texas Water Code. It required the Texas Water Development Board (TWDB) to develop a comprehensive statewide water use plan that incorporated

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Biswa R. Das is research assistant professor, Department of Agricultural Economics, Kansas State University, Manhattan, KS. David B. Willis is associate professor, Department of Applied Economics and Statistics, Clemson University, Clemson, SC. Jeffrey Johnson is assistant professor, Department of Agricultural and Applied Economics, Texas Tech University, Lubbock, TX.

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[1] Comprises the southern third of the Ogallala Aquifer system, which altogether stretches across eight states, encompassing a land area of approximately 10,000 square miles.

locally developed regional water plans (Article 1, Section 1.01). Senate Bill 2 (SB 2) established the Texas Water Advisory Council as well as guidelines to improve management planning of surface water and groundwater at the local, regional, and state levels (Texas Joint Committee on Water Resources, 2002). SB 2 also increased the authority of groundwater districts to regulate the use of groundwater within their jurisdiction, allowing them to impose production fees to limit groundwater withdrawals. These fees could not exceed $1 per acre-foot of water withdrawn. Both bills were collectively designed to transition Texas groundwater management from the rule of capture to a "statutory-based groundwater management system administered by local districts that are tailored to meet the needs of specific aquifers" (House Research Organization, 2000, p. 8).

Several authors have studied the economics of groundwater use in the THP (Arabiyat, 1998; Das, 2004; Feng, 1992; Johnson, 2003; Nieswiadomy, 1985; Terrell, 1998; Wheeler, 2008). Although these studies accounted for the spatial differences in cropping patterns, crop yields, water use, and water supplies between counties, they modeled the Southern Ogallala Aquifer as a homogenous resource at the county geographic level (Das, 2004). Because aquifer drawdown levels,[2] recharge rates,[3] saturated thickness,[4] and water table[5] elevation vary from one locale to another within each county, average county hydrologic conditions are likely not representative of all areas within a county. Similarly, water use is also not similar across all regions within a county. Thus, using average conditions and homogeneous water use could either over- or underestimate policy cost, economic returns, and quantity of groundwater conserved estimates under policies that change the economic incentive to withdraw groundwater. For example, in Gaines County, one of the 19 counties in the study, the per-acre annual return in Year 50 was $65.2 and $31.5 under the normative economic and integrated models, respectively (Das, 2004). Similarly, total annual water use in Year 50 was 226 thousand acre-feet and 83 thousand acre-feet under the economic and integrated models, respectively (Das, 2004).

Appreciating the need to account for such spatial variation is water use, Willis and Whittlesey (1998) developed a two-stage modeling procedure to analyze a variety of hydrologically viable streamflow augmentation policies in the Walla Walla River Basin situated in southeastern Washington and northwestern Oregon. The first-stage economic submodel determined optimal on-farm response to a specific instream flow policy. The second-stage hydrology model used the optimal water use pattern as determined by the economic model to monitor policy effects on monthly streamflow levels and groundwater levels. Stovall (2001) developed a groundwater hydrology model for the THP counties by laying a grid that consisted of 1-square mile cells over the Ogallala Aquifer in the THP. He simulated the impact on the aquifer water volume over time as a result of groundwater withdrawals, primarily for agriculture. Although the model had accurate hydrologic data, the groundwater withdrawal that he imposed did not take into account the agricultural producer behavior with respect to water use over time by accounting for the various costs and returns associated and constrained by the amount of water available and the depth from which water was pumped.

There have been several studies conducted in the state of Texas that focused on alternate types of policies to conserve groundwater. Guerroro, Amosson, and Almas (2008) pointed out the involvement of stakeholders in all phases of the project process as critical, especially when dealing with controversial issues such as water conservation strategies/policies. According to them, this ensures that the appropriate conservation strategies are being evaluated and that realistic implementation schedules are being

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[2] A lowering of water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of groundwater from wells.

[3] The rate at which water flows into the aquifer mainly from precipitation, melting of snow, irrigation runoff, and other domestic and commercial water use runoff.

[4] The difference between the base of the aquifer and the water table elevation.

[5] The surface of an aquifer at which the pore water pressure is atmospheric. It can be measured by installing shallow wells extending a few feet into the zone of saturation and then measuring the water level in those wells.

modeled. It also increases the likelihood of public acceptance of project results. Using information from stakeholders will aid an integrated approach in estimating realistic policy cost and water conserved.

Wheeler et al. (2008) use a short-term and long-term water buy-out policy to estimate the economic impact on production agriculture in the THP. Although the long-term buy-out permanently converts irrigated acreage into dryland, the short-term approach allows returning back to irrigation after a 15-year gap. Based on the findings in one of the representative counties, the short-term cost of saving a foot of saturated thickness was $190 and the long-term cost was $122. As we observe in the findings, these policy costs are significantly higher than either the quota or tax policy considered in our study. More so, it is highly unlikely that producers will switch to a nonirrigated farming knowing very well it is in their economic interest to use the groundwater beneath their farmland.

Keplinger et al. (1998) examined a dry year irrigation suspension as a way of reallocating water when aquifer levels are low for the Texas Edwards Aquifer. In such a scenario, farmers would be paid to suspend irrigation to allow more spring flow or nonagricultural pumping. Their findings suggest that most acreage participates when a $90 per-acre payment is offered before the cropping season. However, considerably higher payments are needed and less water saved for a suspension program instituted during the cropping season.

In this study, we develop an integrated regional water policy model of production agriculture for the THP by linking a dynamic economic optimization model to a detailed hydrology model of the southern portion of Ogallala Aquifer beneath the THP. The 19 shaded counties in Figure 1 that overlay the southern portion of the Ogallala Aquifer account for over 90% of the total groundwater withdrawals from the Ogallala Aquifer in the THP (TWDB, 2005). The integrated model was used to study the impact of two water conservation policies, a tax and a quota policy, and alternate crop price scenarios on agricultural water use that are described in Table 1. The regional differences are demonstrated by comparing countywise economic returns and water use. The conservation policy cost, quantity of water conserved, and cost per acre-foot of water conserved by a county and the region under the tax and quota policies allow us to determine the effectiveness of the two policies.

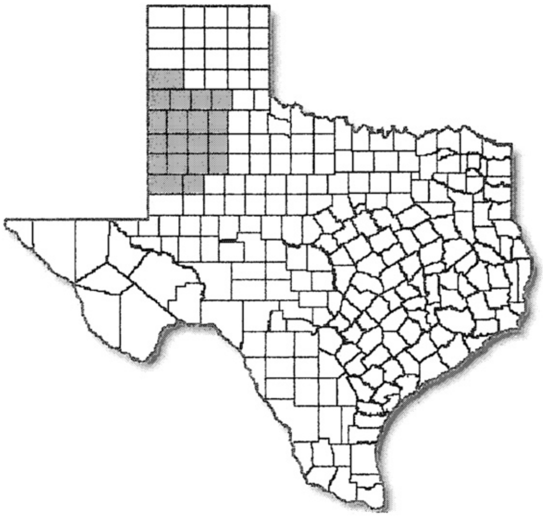

Figure 1. Nineteen-County Study Region in the Texas High Plains (Source: Johnson, 2003, p. 91; Note: The map represents the state of Texas and its counties. The shaded counties in west Texas are among the counties that overlay the southern portion of the Ogallala Aquifer. These 19 counties account for over 90% of the total groundwater withdrawals from the Ogallala Aquifer in the Texas High Plains)

Data and Model Specification

Conceptually, the integrated model consists of three linked submodels. Figure 2 illustrates the data flow among and linking of the three submodels. The following section discusses the data requirements and each of the three submodels independently and explains how they are linked together.

Dynamic Economic Optimization Submodel

The first-stage economic model used in this study is a dynamic nonlinear model of production agriculture for each of the 19 individual

Table 1. Policy Scenarios Examined in the Study Using the Integrated Model

Scenario	Description
Baseline	The baseline scenario simulates agricultural crop response and groundwater use over the 50-year planning horizon assuming optimal producer response to increasing water scarcity over time given current water policy regulations, private economic incentives, and irrigation technology
\$1 tax	Represents the impact of imposing a \$1 tax per acre-foot of groundwater extracted from the Ogallala Aquifer on cropping patterns, groundwater use, and the volume of groundwater stored in the aquifer in Year 50 of the planning period
Policy tax	Represents the tax required to conserve at least 50% of the stored groundwater volume in Year 50 of the planning period beginning with the base year of 2004
Quota	Represents the economic and hydrologic impact of instituting a quota policy designed to assure that at least 50% of initial county reserves are available in each county at the end of the 50-year planning horizon
Average crop prices	Simulates the expected impact on regional economic returns and groundwater use if agricultural crop prices increased to their historic 20-year average prices measured in 2003 dollars
Average crop prices with policy tax	Simulates the effectiveness of the county-specific policy tax developed under the baseline situation assuming crop prices are at their 20-year real average values
High cotton price	The prices of all crops except cotton are returned to their baseline level and cotton price is raised from its baseline value of \$0.57 to \$0.70 per pound
High cotton price with policy tax	The effectiveness of the policy tax established in the baseline simulation is examined to determine its effect of groundwater conservation under a high cotton price scenario.

county-level models in the study area. These counties collectively account for approximately 93% of all Texas groundwater withdrawals from the Southern Ogallala Aquifer (TWDB, 2005) and include Bailey, Briscoe, Castro, Cochran, Crosby, Dawson, Deaf Smith, Floyd, Gaines, Garza, Hale, Hockley, Lamb, Lubbock, Lynn, Parmer, Swisher, Terry, and Yoakum. Furthermore, almost 95% of these withdrawals are for irrigated agriculture with very little municipal use because of water quality considerations in the region (Das, 2004). There is very little industrial use and residential water use in the region is sourced from Lake Meredith. Each county-level model was designed to derive the optimal time path for groundwater extraction that maximized the net present value of agricultural returns (for cotton, sorghum, corn, wheat, and peanuts) over a 50-year planning horizon in each county.

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 is expressed as:

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

where c represents the crop grown, i represents the either irrigated or nonirrigated,[6] 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_{it} 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 type i in period t, L_t represents the pump lift in feet in time t, and NI_t represents the net income in time t. Yield

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[6] In the rest of the article, we use either irrigated or nonirrigated as the two types of irrigation.

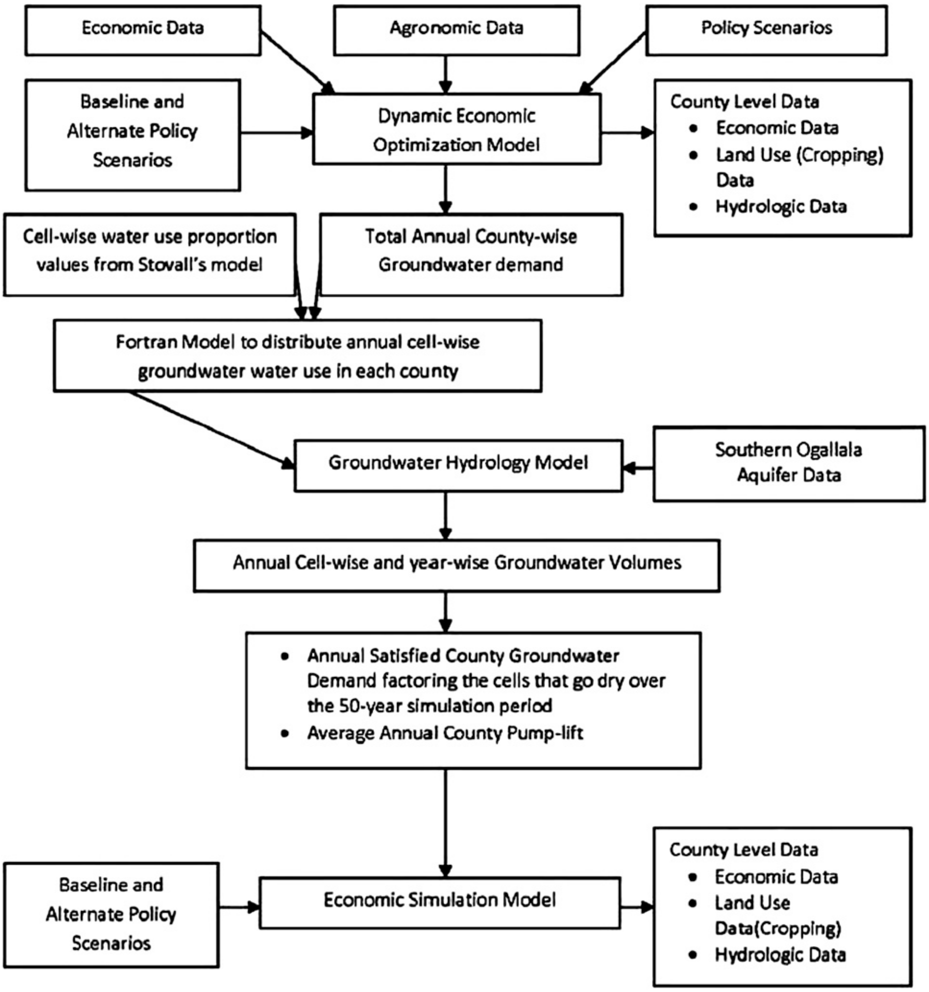

Figure 2. Model Linkages and Data Flow within the Integrated Economic Model

(Y_{cit}) is calculated using the production functions derived from the Crop Production and Management Model (CROPMAN) model.

To develop the production functions using CROPMAN Software (2003) describing crop yield response to applied irrigation water, the following data were used. The variable costs for dryland crop production and the additional costs for irrigation were obtained from crop enterprise budgets developed by the Texas Agricultural Extension Service for Texas Extension District 2 that are included in the Appendix. A low-pressure center pivot irrigation system was used as the representative irrigation system based on information that this technology was the most widely used within the study region (Texas Agricultural Experiment Station, 2003). A brief explanation of how CROPMAN works is provided in the Appendix. Like with every sector that consumes energy, there is a good possibility that energy prices may increase and technological advancements will increase efficiency of irrigation systems and pump/engine. The costs to irrigated agriculture will change based on how much the price increases are compensated by increase in engine and irrigation efficiency. Clearly, the assumptions of only one type of irrigation technology as well as no changes in fertilizer application rates between dryland and irrigated could have impacts on the profitability of the overall enterprise.

We used one equation of motion to monitor pump-lift, which allows the model to capture the impact of agricultural water use on aquifer reserves, pump-lift, pumping cost, and net agricultural returns over the 50-year planning horizon considered. The relationship between management choices (crops irrigated and quantity of water applied per acre) made at time t and the value of the two variables (pumping lift and remaining groundwater stock) at time $t + 1$ is captured using this recursive equation. Assuming that a hydrologic region (the county) is homogeneous, the equation of motion for pump lift at time t for a representative acre is specified as:

$$(2)\qquad L_{t+1} = L_t + 1/SY^*[(W_t - RCH_t)/12],$$

where L_{t+1} is the pump-lift in feet at time $t + 1$, and L_t the pump lift in time period t. The parameter SY is specific yield, the percentage of aquifer volume available for pumping. In the economic submodel, the SY value assigned to each study region county was 0.15, the average value for the Southern Ogallala Aquifer. The variable W_t represents average groundwater withdrawals per irrigated acre in each county measured in ac-in/ac for all irrigated crops, and RCH_t is aquifer recharge in ac-in per acre to the aquifer from all sources, including groundwater return flow. The 12 in the denominator converted inches to feet. It must be noted here that because the lateral flow of water is a slow process, the possibility for rapid withdrawal in one region increasing the pump lift or decreasing the saturated thickness in a neighboring region, although possible, is not very probable in a short timeframe. The rate of groundwater flow is impacted by the viscosity of the water, the porosity of the soil, and the gradient (Fetter, 2001).

The objective function was maximized for a 50-year planning horizon and expressed as:

$$(3)\qquad \text{Maximize } NPVR = \sum_{t=1}^{50} NI_t(1 + r)^{-(t-1)}$$

where NPVR is the net present value of net income and r represents the social discount rate. The findings are extremely sensitive to the discount rate. Using a much greater rate will lead to more counties using up the groundwater in the present time period. A positive discount rate would imply that water is more valuable in the present than in the future. Using a negative discount rate would mean that water has greater value in the future than in the present time. For the purposes of this study, a discount rate of 3% is used. A brief explanation of why we choose a 3% is presented in the Appendix. The dynamic optimization model can be represented as:

Maximize

$$(4)\qquad \begin{aligned} NPVR = \sum_{c}\sum_{i}\sum_{t} \Theta_{cit}\{(P_c Y_{cit}) \\ - C_{cit}(WP_{cit}, L_t)\}(1 + r)^{-(t-1)}, \end{aligned}$$

The objective function in Equation (4) was obtained by substituting Equation (1) into Equation (3).

Equations (5), (6), and (7) express the relationship between the amount of water used and the amount of water available. Equation (5) expresses the amount of water available to be pumped as gross pumping capacity (GPC_t) in period t, where ST_t represents the saturated thickness in time t, IST is the initial saturated thickness, WY is the average initial well yield for the county expressed in gallons per minute, AW is the average number of wells per irrigated acre of the county, and 4.42 acre-inches per gallon per minute is a factor developed from the assumption of 2000 pumping hours in a growing season. Equation (6) expresses the total amount of water pumped per acre (WT_t) as the sum of water pumped on each crop. Equation (7) 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).

$$(5)\qquad GPC_t = (ST_t/IST)^2 * (4.42 * WY/AW),$$

$$(6)\qquad WT_t = \sum_{c}\sum_{i} \Theta_{cit} * WP_{cit},$$

$$(7)\qquad WT_t \leq GPC_t,$$

Equation (8) 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 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. Equation (9) expresses the cost of production (C_{cit}) for crop c produced by irrigation type i in period t, where VC_{ci} is the variable cost of production per acre, HC_{cit} is the harvest cost per acre, MC_i is the maintenance cost per acre for the single type 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 irrigation.

$$(8)\quad PC_{cit} = \{[EF(L_t + 2.31*PSI)EP]/EFF\}*WP_{cit}$$

$$(9)\quad \begin{aligned} C_{cit} &= VC_{ci} + PC_{cit} + HC_{cit} + MC_i \\ &\quad + DP_i + LC_i, \end{aligned}$$

Equation (10) limits the share of acres for all crops *c* produced by irrigation type *i* for each period t to be less than or equal to 1. Equation (11) 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 to replicate an orderly transition between crop enterprises. Equation (12) ensures that the values of the decision variables are nonnegative.

$$(10)\quad \sum_c \sum_i \Theta_{ci} \leq 1 \quad \text{for all } t$$

$$(11)\quad \Theta_{cit} \geq 0.9\Theta_{cit-1} \quad \text{and}$$

$$(12)\quad \Theta_{cit} \geq 0$$

To estimate the impact on economic returns and water use of the two tax policies, $1 tax policy, and the policy tax required to achieve at least 50% aquifer storage at the end of the 50-year planning period, the tax rates were introduced in the cost equation (Equation [9]) where the tax rate (either $1 or the policy tax) expressed in dollars per ac-ft/ac was multiplied by the amount of water used in ac-ft/ac. Similarly, to estimate the impact of the quota policy, the quota rate of 50% was introduced as a constraint that restricted the saturated thickness at 50% of the initial saturated thickness at the end of the 50-year planning period in each county.

Hydrologic Submodel

Stovall's (2001) hydrology model calibrated for the Southern Ogallala Aquifer was used to model aquifer status. MODFLOW, a widely used computer software program designed to simulate groundwater impacts caused by hydrologic stresses, was used to observe changes in water table elevation and the volume of water storage in each of the cells in the grid (McDonald and Harbaugh, 1988). The entire study region was divided into a grid of 1-square mile cells that were overlaid on the study region counties. These cells were the unit of analysis and county aquifer groundwater storage estimates over the 50-year planning horizon were calculated by aggregating the values corresponding to the county-specific cells. Based on the initial water head, the water use, recharge, saturated thickness, hydraulic conductivity, and other physical characteristics of the aquifer in that cell, the 1-square mile cells either continue to be operational or dry up over time. Once a cell is dry, it remains so for the rest of the simulation years.

The annual county-level time-series of optimal groundwater withdrawals generated by the first-stage economic model for the 50-year planning horizon for each of the 19 study area counties was directly written into an Excel spreadsheet (Microsoft, Redmond, WA) using the GAMS data export commands. The annual water use data for each county was subsequently spatially distributed over the land area in each county for each simulated year. The weighting scheme was developed using detailed irrigation survey maps provided by High Plains Underground Water Conservation District #1 and the South Plains Underground Water Conservation District that inventoried the location of each center pivot irrigation system in use in 1999 (Stovall, 2001). A detailed explanation of the weighting scheme is provided in the Appendix. Groundwater Vistas Version 3 (ESRI, 2001), a Windows-based graphic interface computer program, which can access MODFLOW, was used to execute each policy simulation for the spatially distributed groundwater stresses predicted by the normative economic model. The resulting output was exported as shape files, which were accessed using ARCGIS software (Environmental Systems Research Institute, 2003) to estimate the volume of water in each grid cell that still had water and eliminate those cells that went dry over time. A brief explanation on how the hydrology model iteratively simulated water heads level in each cell is included in the footnotes.

Economic Simulation Submodel

The structure of the third-stage economic simulation submodel was similar to the first-stage normative economic submodel with two major differences. First, the equation of motion was deleted in the economic simulation model. Second, the county estimates of annual groundwater withdrawals and the average pump-lift derived from the hydrology simulation were imported into the economic simulation model as parameter values instead of variables.

It is significant to mention here that the study assumes that all wells within a county were equally productive in the initial year of the optimization procedure. Under identical hydrologic conditions, each irrigation system was assumed to have the same efficiency and pumping capacity at a point in time. Although a necessary assumption, it limits the analysis to a degree given that center pivot systems within a county have varying levels of efficiency.

Policy Scenarios Examined

Table 1 illustrates all the scenarios that were evaluated in this study. We estimate the cost-effectiveness of using either production quotas and/or fees (taxes) designed to influence economic behavior of agricultural producers to preserve 50% of the current total capacity of groundwater over a 50-year planning horizon. Maintenance of 50% of the initial groundwater reserve levels is a management policy being considered by both Panhandle Groundwater Conservation District and High Plains Underground Water Conservation District, the two largest groundwater management districts in the THP. We also examine the impact that changes in major crop prices, including cotton, wheat, sorghum, corn, and peanuts, have on groundwater usage in the THP. Overall the study examines seven scenarios excluding the baseline: $1 tax, policy tax, quota, average crop price, average crop price with policy tax, high cotton price, and high cotton price under policy tax.

Besides the tax and quota policies examined to ensure 50% aquifer storage at the end of the 50-year planning horizon, the study considered two price scenarios that involved two variants of a crop price increase. In the first price increase scenario, crop prices were set at their real 20-year average prices. The calculated real per unit prices for cotton, corn, sorghum, peanuts, and wheat used were $0.62, $2.77, $0.04, $0.28, and $3.33, respectively (Texas Agricultural Statistics Service, 2002). Under the second price scenario, all crop prices except cotton were returned to their original lower baseline values, but cotton price was set at $0.7 per pound. In real terms, a $0.7 per pound lint price has only been exceeded twice in the last 20 years in 1984 and 1995 (Texas Agricultural Statistics Service, 2002), but given the importance of cotton production to the THP, this scenario was designed to establish the likely maximum agricultural use of groundwater within the THP over the next 50 years.

Findings

Imposition of a tax of $1/ac-ft water use reduced the 50-year per-acre net present value return in each county relative to the baseline. As shown in Table 2, the decrease ranged from a low of $4 in Dawson County to a high of $25 in Hale County. Overall, at the regional level, the $1 use tax, reduced the 50-year per acre net present value return stream by $14, or approximately 1% per acre. Regionally, groundwater use was reduced by only 0.5% relative to baseline use over the 50-year planning horizon. Moreover, despite the imposition of the $1 use tax, four counties (Briscoe, Deaf Smith, Gaines, and Swisher, marked with asterisk in Tables 2–5) had less than 50% of their initial groundwater reserves in storage at the end of the simulation period. Overall, the hydrologic impact of the $1 use tax was not significantly different from the baseline scenario.

For the four counties whose ending reserve levels were less than 50% of their initial level, the tax rate per acre-foot was increased to the point where at least 50% of initial reserves remained in storage at the end of the simulation. The tax rate was derived by iterating the integrated model repeatedly until we found an alternative tax rate that conserved at least 50% (rounded to nearest decimals) of initial year groundwater reserves. This tax was labeled as a policy tax.

Table 2. Change in Per-Acre Net Present Value Returns Over the 50-Year Planning Horizon

County	Baseline	$1 Tax	Policy Tax	Quota	Historical Prices	Historical Prices Policy Tax	High Cotton Price	High Cotton Price Policy Tax
Bailey	0.00	–19.86	–19.86	0.00	482.76	463.65	1030.32	1010.07
Briscoe*	0.00	–14.76	–855.38	–489.09	394.84	–569.55	678.92	–366.71
Castro	0.00	–19.04	–19.04	0.00	498.94	479.78	1023.96	1005.34
Cochran	0.00	–10.84	–10.84	0.00	307.37	296.63	504.64	494.25
Crosby	0.00	–17.60	–17.60	0.00	624.27	606.48	1385.10	1367.21
Dawson	0.00	–4.12	–4.12	0.00	168.00	163.75	266.39	262.23
Deaf Smith*	0.00	–20.37	–174.91	–8.70	479.43	308.87	999.87	835.85
Floyd	0.00	–21.63	–21.63	0.00	669.73	648.60	1484.78	1463.77
Gaines*	0.00	–16.84	–1045.80	–22.73	284.80	–757.35	148.67	–926.26
Garza	0.00	–6.88	–6.88	0.00	314.75	307.93	611.74	604.35
Hale	0.00	–25.36	–25.36	0.00	762.40	736.93	1719.80	1695.30
Hockley	0.00	–9.87	–9.87	0.00	304.23	294.37	584.17	575.04
Lamb	0.00	–21.62	–21.62	0.00	723.15	701.51	1609.17	1588.15
Lubbock	0.00	–13.23	–13.23	0.00	404.73	391.88	857.97	844.59
Lynn	0.00	–5.88	–5.88	0.00	292.92	286.11	505.48	499.11
Parmer	0.00	–4.80	–4.80	0.00	469.17	450.03	1074.74	1056.20
Swisher*	0.00	–7.51	–338.36	–80.13	290.67	–46.88	492.16	163.07
Terry	0.00	–8.99	–8.99	0.00	277.37	268.53	338.37	329.68
Yoakum	0.00	–13.13	–13.13	0.00	431.12	418.82	599.27	587.39
Regional	0.00	–13.81	–137.75	–31.61	430.56	286.85	837.66	688.88

Note: In Tables 2–4, an asterisk after a county name identifies counties with less than 50% of their initial groundwater storage volume at the end of the 50-year simulation under baseline conditions (Year 2004). In those counties, the optimal groundwater tax is defined as the tax required to conserve 50% of initial county groundwater reserves under the baseline condition when a $1 tax level was insufficient; in all other counties, the tax was set at the legal maximum of $1 per acre-foot.

The policy tax on groundwater withdrawals for the four counties ranged from a low of $9 in Deaf Smith to a high of $77 in Briscoe. In Gaines and Swisher, the tax was $63 and $45, respectively. The tax rates varied depending on the value of crops grown, available groundwater supplies, crop substitution options, and the area under irrigated acreage. Although the per-acre net present value return was identical to the prior $1 per acre-foot tax scenario for the 15 counties, they were much lower for the four counties that levied the higher tax primarily as a result of the magnitude of the policy tax required to achieve the 50% conservation goal. Regionally, groundwater use declined by approximately 6% under this scenario.

Ironically, the percentage share of county cropland under irrigation at the end of the planning horizon was slightly larger than their ending share under the baseline for three of the four counties confronted with a tax in excess of $1/ac-ft. This occurred despite the fact that these counties used less groundwater overall than they did under the baseline scenario. This phenomenon occurred because groundwater reserves are subject to reserve dependent costs, that is, marginal extraction cost increases as reserves are diminished. Moreover, groundwater reserves are also subject to a stock effect in the sense that recharge augments storage over time. Thus, when use is restricted, the optimization model finds it more profitable to use a greater share of allowed groundwater use at the end of the planning horizon because the in situ value of the reserves is growing more rapidly than the rate of discount. The in situ value increases because the scarce groundwater supplies are reserved for more valuable future uses and this initial conservation reduces the cost of extracting future reserves because pump lifts are not as deep.

A 50% quota on ending water reserves was not restrictive in the 15 counties that had reserves in excess of 50% of their initial groundwater reserves at the end of the baseline

Table 3. Percent Change in Total Net Present Value Relative to the Baseline Condition Over the 50-Year Planning Horizon by Policy Scenario, County, and Region

County	$1 Tax	Policy Tax	Quota	Historical Prices	Historical Prices Policy Tax	High Cotton Price	High Cotton Price Policy Tax
Bailey	–2.21%	–2.21%	0.00%	53.62%	51.49%	114.43%	112.18%
Briscoe*	–0.80%	–46.06%	–26.34%	21.26%	–30.67%	36.56%	–19.75%
Castro	–2.19%	–2.19%	0.00%	57.38%	55.17%	117.75%	115.61%
Cochran	–0.88%	–0.88%	0.00%	24.90%	24.03%	40.89%	40.05%
Crosby	–1.89%	–1.89%	0.00%	67.15%	65.24%	149.00%	147.07%
Dawson	–2.63%	–2.56%	0.00%	107.00%	104.29%	169.67%	167.02%
Deaf Smith*	–3.64%	–31.28%	–1.56%	85.73%	55.23%	178.79%	149.46%
Floyd	–1.72%	–1.73%	0.00%	53.19%	51.52%	117.93%	116.26%
Gaines*	–0.81%	–50.06%	–1.09%	13.63%	–36.25%	7.12%	–44.34%
Garza	–0.66%	–0.66%	0.00%	30.43%	29.77%	59.13%	58.42%
Hale	–1.47%	–1.45%	0.00%	44.11%	42.64%	99.51%	98.09%
Hockley	–1.67%	–1.67%	0.00%	51.49%	49.82%	98.87%	97.32%
Lamb	–1.88%	–1.88%	0.00%	62.85%	60.97%	139.85%	138.02%
Lubbock	–1.75%	–1.75%	0.00%	53.49%	51.79%	113.39%	111.63%
Lynn	–0.52%	–0.52%	0.00%	25.90%	25.30%	44.70%	44.14%
Parmer	–0.84%	–0.83%	0.00%	81.93%	78.59%	187.68%	184.44%
Swisher*	–0.71%	–31.90%	–7.56%	27.41%	–4.42%	46.40%	15.38%
Terry	–0.50%	–0.48%	0.00%	15.38%	14.89%	18.77%	18.29%
Yoakum	–0.54%	–0.54%	0.00%	17.89%	17.38%	24.87%	24.38%
Regional	–1.25%	–11.75%	–1.27%	38.63%	26.69%	75.38%	63.20%

simulation and imposed no policy costs. In each of these 15 counties, per-acre net present value over the 50-year planning horizon and groundwater use was identical to their respective baseline level. Therefore, a quota policy did not impact the decision-making of agricultural producers in these counties. However, the 50-year returns were lower in the four counties where the water use constraint was binding. The lower economic return level reflects the policy induced groundwater scarcity in each of these four counties. Regionally, groundwater use declined by approximately 5% under a quota policy. Despite the lower economic return, producers in these counties were much better off than they were under both the $1 tax and policy tax scenarios. From a regional perspective, across all 19 counties, the conservation tax policy reduced the present value of net income by 12%, whereas the quota policy reduced the present value by only 1.3% relative to the baseline condition as shown in Table 3.

The average crop price scenario simulated the expected impact on regional economic returns and groundwater use if agricultural crop prices increased to their 20-year average prices measured in 2003 dollars. As shown in Table 3, regionally, per-acre net present value increased by 39% relative to the baseline. For individual THP counties, the increase ranged from a low of 14% in Gaines to a high of 107% in Dawson. As expected, irrigated groundwater diversions increased with crop prices by approximately 4% across the region (Table 4).

Regionally, imposing the policy tax dampened the increase in both per-acre net present value and water use resulting from the higher crop prices, but both remained higher than their untaxed baseline values. As shown in Table 3, per-acre net present value was 27% larger, with the tax and higher crop prices than in baseline, vs. 39% larger with higher prices and no groundwater tax. Although imposition of the conservation tax reduced regional groundwater use by 1.3%, groundwater use remained 2.6% higher than in the baseline situation and 3.1% higher than in the baseline with the conservation tax (Table 4).

Table 4. Percent Change in Total Groundwater Use in the Texas High Plains by County and Policy Scenario

County	$1 Tax	Policy Tax	Quota	Historical Price Baseline	Historical Price Policy Tax	High Cotton Price	High Cotton Price Policy Tax
Bailey	–0.41%	–0.41%	0.00%	1.63%	1.26%	3.32%	2.98%
Briscoe*	–0.37%	–65.55%	–72.06%	1.55%	–24.64%	3.03%	–20.80%
Castro	–2.91%	–2.91%	0.00%	2.78%	2.78%	2.72%	2.72%
Cochran	–0.02%	–0.02%	0.00%	–0.18%	–0.20%	–0.46%	–0.49%
Crosby	–0.29%	–0.29%	0.00%	2.32%	2.06%	4.83%	4.60%
Dawson	–0.43%	–0.43%	0.00%	1.01%	0.62%	2.10%	1.76%
Deaf Smith*	–0.11%	–17.94%	–15.37%	0.18%	–0.71%	0.22%	–0.46%
Floyd	–0.02%	–0.02%	0.00%	–0.10%	–0.11%	–0.28%	–0.29%
Gaines*	–0.06%	–8.83%	–6.12%	0.03%	–6.72%	2.39%	–0.30%
Garza	–0.29%	–0.29%	0.00%	0.96%	0.70%	2.00%	1.77%
Hale	0.00%	0.00%	0.00%	–0.01%	–0.01%	–0.02%	–0.02%
Hockley	–0.01%	–0.01%	0.00%	–0.10%	–0.11%	–0.29%	–0.30%
Lamb	–0.07%	–0.07%	0.00%	–0.23%	–0.30%	–0.60%	–0.65%
Lubbock	0.00%	0.00%	0.00%	–0.02%	–0.03%	–0.07%	–0.07%
Lynn	–0.26%	–0.26%	0.00%	0.62%	0.39%	1.28%	1.06%
Parmer	–13.41%	–13.41%	0.00%	182.22%	182.21%	182.11%	182.11%
Swisher*	–0.01%	–30.83%	–34.31%	–0.09%	–0.49%	–0.27%	–0.67%
Terry	–0.03%	–0.03%	0.00%	0.50%	0.49%	0.45%	0.45%
Yoakum	–0.05%	–0.05%	0.00%	0.06%	0.01%	0.08%	0.04%
Regional	–0.51%	–5.66%	–4.94%	3.98%	2.62%	4.43%	3.56%

Imposing the policy tax under historical average crop prices had a marginal effect in reducing groundwater use relative to their untaxed baseline groundwater use level. As expected, each county used more groundwater than they did under baseline prices with the imposition of the conservation tax. As shown in Table 4, under the historical average price scenario, the conservation tax failed to conserve 50% of initial groundwater supplies in each of the four counties where the conservation tax had been raised beyond the current legal maximum limit of $1 per acre-foot to achieve the 50% conservation goal. Swisher and Deaf Smith had 40% and 36%, respectively, of their initial groundwater reserves at the end of the 50-year planning horizon with the policy tax imposed. This suggests that demonstrating that the effectiveness of any groundwater conservation tax is heavily influenced by market prices for crops. How a county adjusts to changes in crop prices is a function of the economic, agronomic, and hydrologic parameters governing the individual county.

Given the agricultural importance of cotton production to the THP, it was not surprising to find that over the 50-year simulation, regional per-acre net present value was 75% larger under the high cotton price scenario relative to the untaxed historical average price scenario (Table 3). In real terms, a $0.70 per pound lint price has only been exceeded twice in the last 20 years ($0.75 in 1995 and $0.71 in 1984; Texas Agricultural Statistics Service, 2002), but given the importance of cotton production to the THP, this scenario was designed to establish the likely maximum agricultural use of groundwater within the THP over the next 50 years. Moreover, at the county level, per-acre net present value was larger in all 19 counties modeled relative to the untaxed historical average price scenario. Economic returns in Gaines County were lower because it specialized in high-valued peanut production, and the increase in cotton price was an insufficient incentive to substitute irrigated cotton acreage for high-value irrigated peanut acreage. Regional economic returns were 75% larger than they were in the baseline and individual county increases relative to the baseline ranged from a low of 7% in Gaines County to a high of 187% in Parmer County (Table 3). As previously noted, at higher cotton prices, Parmer County reversed its baseline trend of transitioning into dry land wheat over time, and Gaines County almost exclusively stays in irrigated peanut and cotton production.

As shown in Table 4, total regional water use was approximately 4.4% more than it was under the 50-year baseline condition and all counties increased their groundwater use. Overall, relative to the baseline, individual county groundwater use increases ranged from a low of 0.3% in Lamb County to a high of 182% in Parmer County. The change in the county groundwater use pattern relative to the baseline condition closely parallels the distributional pattern of the previously discussed historical average price scenario.

Despite imposition of the conservation tax, regional groundwater use was still 3.6% higher than in the baseline simulation and nearly as large as it was in the untaxed historical average price scenario. Moreover, the conservation tax was an insufficient incentive for four counties to conserve 50% of initial groundwater reserves. Groundwater conservation was considerably below the 50% conservation target in each of the four counties where the tax rate was increased above the legal $1 per acre-foot maximum value under baseline conditions. Three of the four counties had less than 40% of their initial reserves at the end of the simulation.

As a result of the significant contribution of cotton acreage to cropland returns in the THP, it was not surprising to find that average per-acre net present values were larger in 17 of the 19 counties relative to the untaxed baseline return. Only Briscoe and Gaines counties had lower per-acre net present values than in the untaxed baseline. This is attributable to the empirical finding that under baseline conditions, these two counties found it more profitable to increasingly specialize in peanut production over time and limit cotton acreage to a rotational crop. Given the high value of groundwater in peanut production under the baseline condition, these three counties remained better off paying the additional tax despite the adverse impact it has on farm profitability than to significantly reduce groundwater use and/or increase cotton acreage.

It is interesting to note that under the two alternate price scenarios considered, the groundwater use in some counties was actually lower than under the original baseline. For example, in Lubbock County, under the historical average price scenario, the crop mix changed from producing more irrigated cotton to producing more nonirrigated wheat. As a result of this changed mix, the total groundwater use over the 50-year planning horizon declined compared with the original baseline. Similarly, under the higher cotton price scenario, the crop mix remained the same for the first 20 years, but as a result of the higher cotton prices, returns were significantly higher. Under the higher cotton price scenario, irrigated cotton continued to dominate until Year 24, i.e. for 4 additional years, resulting in a significant increase in the net present value of returns for the county. Furthermore, it continued to have marginally higher acreage until the end of Year 50 relative to the initial baseline. It was observed that the higher cotton prices did not significantly increase cotton farming, although the economic returns were significantly higher. Groundwater use was lower by only 0.03%, which over a 50-year planning horizon may be very insignificant. In the seven counties that showed this trend, groundwater use declined between 0.6% and 0.02% relative to the baseline (Table 3). Given that the planning horizon comprised 50 years, this could be treated as an insignificant effect.

Acre-Foot Cost of Conserved Water

The conservation policy cost, quantity of water conserved, and cost per acre-foot of water conserved by a county and the region for the conservation tax policy and for the quota policy are presented in Table 5. It is important to note that from a theoretical perspective, both the conservation tax policy and the quota policy should provide an identical level of conservation. However, from an empirical perspective, time and computer resource constraints limited the number of iterations used to find the conservation tax and quota level for each county that would bring about convergence. Thus, the values presented are approximations to the level of water that would be conserved under an exact tax and quota. Although

Table 5. Net Present Value Policy Cost, Conserved Groundwater, and Net Present Value Policy Cost per Acre-Foot Conserved Water for Baseline Condition: Policy Tax vs. Quota Policy by County and Region

	Net Present Value Cost ($)		Conserved Water (ac-ft)		Cost per ac/ft	
County	Tax	Quota	Tax	Quota	Tax	Quota
Bailey	4,332,093	0	34,121	0	127	0
Briscoe*	81,460,568	46,577,354	2,426,215	2,666,959	34	17
Castro	7,103,749	0	310,655	0	23	0
Cochran	2,304,419	0	1,503	0	1,533	0
Crosby	4,801,602	0	30,488	0	157	0
Dawson	1,563,536	0	18,400	0	85	0
Deaf Smith*	59,639,834	2,965,923	3,060,206	2,622,398	19	1
Floyd	7,287,302	0	2,259	0	3,226	0
Gaines*	464,089,391	10,084,633	1,695,200	1,174,641	274	9
Garza	352,661	0	2,705	0	130	0
Hale	10,125,838	0	32	0	313,614	0
Hockley	3,654,596	0	583	0	6,266	0
Lamb	7,580,003	0	9,546	0	794	0
Lubbock	4,738,838	0	149	0	31,812	0
Lynn	2,177,910	0	17,281	0	126	0
Parmer	1,624,975	0	492,831	0	3	0
Swisher*	98,226,395	23,262,492	2,622,732	2,918,183	37	8
Terry	3,093,409	0	3,275	0	944	0
Yoakum	2,727,917	0	4,335	0	629	0
Total	766,885,037	82,890,402	10,732,516	9,382,181	71	9

Note: Counties represented by an asterisk required more than a $1 per acre-foot tax to conserve 50% of the aquifers existing storage at the end of Year 50. Appendix

both policies conserve approximately the same amount of groundwater, the total regional cost of the conservation tax policy to production agriculture is approximately eight times larger than for the quota policy. At the regional level, each acre-foot of groundwater conserved under the conservation tax policy costs $71 compared with the quota policy cost of $9. Moreover, there was significant variation in the average policy cost by county.

Conclusion and Implication

The estimated economic cost and attained water conservation were significantly different between the preliminary first-stage and final third-stage estimates, indicating the importance of controlling for aquifer heterogeneity in groundwater policy research. Relative to the baseline policy, the $1 per acre-foot tax policy did not result in a significant level of groundwater conservation. Regionally, the policy tax reduced the net present value of agricultural returns by 19.97% relative to the baseline, but only conserved 2.61% of regional groundwater reserves under baseline conditions. Given the high agricultural cost of the policy tax, a quota restriction was imposed on groundwater use in each county to ensure that groundwater reserves did not decrease below 50% of their initial level in each county under baseline conditions. It was observed that most counties in the THP will economically exhaust the aquifer before physical depletion occurs. The quota policy reduced regional net income by only 2.29% and conserved the same quantity of water as the policy tax. Both the $1 tax policy and the quota policy conserve approximately the same amount of groundwater, but the total regional cost of the policy tax to production agriculture is eight times larger than for the quota policy. The last four scenarios considered involved two variants of a crop price increase. As expected, groundwater use increased under both price scenarios, and the policy tax was ineffective in curbing groundwater use. In fact, even with imposition of the policy tax, groundwater use was larger in both price change scenarios than in the untaxed baseline condition. Clearly the effectiveness of any groundwater conservation tax is heavily influenced by crop market prices. How a county adjusts to changes in crop prices is a complex function of the economic, agronomic, and hydrologic parameters governing the individual county.

Based on the findings of the study, the choice of whether to implement a tax or quota policy should ultimately depend on the management perspective. If one is interested in minimizing the cost to production agriculture, then the quota policy is the preferred choice assuming administration and enforcement costs are the same under both policies. However, if administration and enforcement cost are high, a management agency may prefer the tax policy because it generates revenues that can be used to administer the conservation program. Moreover, the conservation management agency might wish to use any tax policy revenues generated in excess of their administration costs to purchase groundwater rights.

Irrespective of the type of policy being studied, the value of the integrated modeling framework is in its ability to fully combine economic factors and physical responses to behaviorally driven hydrological stresses. The analytic framework maintains spatial variability to capture changes in the aquifer's stored water resources and water table elevation within the region. It is also able to account for heterogeneous land use patterns within a county. Development of such a policy model possibly enhances the credibility of economic costs and benefits and water conservation estimates developed by policymakers. It simultaneously considers water conservation policies at a subregional level. Besides the two policies examined in this study, other potential applications for the water policy model could include investigations into the economic and hydrologic impact of interbasin water market transfers, increased irrigation efficiency, and increased irrigation delivery system efficiency, all targeting water conservation.

In future research, the availability of more microlevel data would improve the ability to accurately perform a detailed county level analysis. Research of this type will be further enhanced by incorporating advanced GIS data collection techniques to gather information on crop cover, well locations, management techniques, and crop yields. The activity set of the model can be increased to consider livestock options, conservation reserve program options, and environmental management options such as managing for the wildlife and water fowl values. Given the high value of water in the commercial and residential sectors, the activity set within the model needs to be broadened to consider the benefits and costs associated with intersectoral market transfers. The initial model would also benefit if the set of irrigation technologies included in the model were broadened. Moreover, as additional detailed data are collected, additional agronomic and or marketing constraints might need to be added to more fully model producer decision-making. The role of crop portfolio management as a producer risk management tool would also enhance the model.

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Appendix

Data Included in the Model

Energy data included an energy use factor for electricity of 0.164 KWH/feet of lift per acre-inch, system operating pressure of 16.5 pounds per square inch, energy price of $0.0633 per KWH, and pump/engine efficiency of 50%. Other costs included 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/hr, annual maintenance cost of 8% of initial cost, and a discount rate of 3%.

CROPMAN

CROPMAN is a Windows-based application of the Environmental/Policy Integrated Climate (EPIC) model originally developed by USDA-ARS that simulates the interaction of natural resources (soil, water, and climate) and crop management practices on crop yield, soil properties, soil erosion, and nutrient/pesticide leaching. CROPMAN requires the user input data on crops planted, irrigation systems, soil types, management practices, and weather data. CROPMAN was used to develop county-specific irrigated crop production functions for the five dominant irrigated crops in the 19 county region). The yield data needed to estimate each county-specific crop water response function were generated holding the production techniques and the timing of cultural practices constant, in each individual county, and allowing only the quantity of applied irrigation water to vary. Irrigation timing was also held constant with the quantity of irrigation water applied evenly divided between the various irrigation dates. Moreover, the simulated yield data were generated under the assumption of average temperature and average precipitation in the growing season. The simulated crop yields were recorded for each water application level and subsequently used to statistically estimate each county-specific crop yield response function assuming a quadratic functional form with per-acre yield as the dependent variable and the acre-inch quantity of applied irrigation water as the independent variable. To provide a dryland alternative to irrigation, average county-specific dryland yields were estimated for each crop under average weather conditions and representative management techniques.

Weighting Scheme

Stovall (2001) developed the series of weights used to distribute projected annual aggregate county groundwater withdrawals over the county aquifer grid comprising each county. The aquifer grid for most counties consisted of approximately 900 1-square mile cells. Stovall developed his weighting scheme by using detailed irrigation survey maps provided by High Plains Underground Water Conservation District #1 and the South Plains Underground Water Conservation District that inventoried the location of each center pivot irrigation system in use in 1999. For each county, Stovall overlaid a transparent copy of the aquifer grid on the irrigation survey maps and counted the number of irrigation systems located in each grid cell. In a given county, the percentage of total county groundwater withdrawn from each cell contained within the county was calculated as the number of quarter mile irrigation systems in the grid cell divided by the total number of irrigation systems within the given county. By design, the sum of the percentage weights used to allocate total water among the grid cells in each county sum to one.

Social Rate of Time Preference

"The social rate of time preference is the rate at which society is willing to substitute present for future consumption of natural resources. The federal opportunity cost of capital and the rate of productivity growth are commonly used as proxies for the social rate of time preference. When using the federal cost of capital, the generally accepted practice is to apply the effective yield on comparable-term Treasury securities (e.g., 20-year Treasury bonds for a study with a 20-year analysis timeframe). During the decade of the 1990s, the average 10-year Treasury bond rate was 6.01%, whereas inflation averaged 2.88%. Thus, the real rate of interest on Treasury bonds was roughly 3.13% during the 1990s. Social policy is also concerned with an equitable distribution of consumption over time. Based on this premise, the rate of productivity growth can be used as a proxy for the social rate of time preference. This policy reflects the opportunity cost argument that the incremental or marginal benefit to the country generated by the public project should grow as fast as the productive capacity of industry. From 1990 to 2003, real Gross Domestic Product grew by 2.96%. Thus, using productivity over that period as the basis of the discount rate generates a roughly 3.0% rate" (National Oceanic and Atmospheric Administration, 2010).