Economic Optimization Models to Project Income and Hydrological Changes: A Case of Groundwater Management in Texas

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Selected Paper prepared for presentation at the
International Conference on Policy Modeling (EcoMod 2008)
Berlin, Germany, July 2-4, 2008

Partial Funding for this project was provided by
Ogallala Aquifer Initiative, USDA-ARS, Bushland, Texas and
Dryland Agricultural Institute, West Texas A&M University, Canyon, Texas

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Abstract: An economic optimization model for a 60-year planning horizon is being developed using available groundwater resources in the Texas Panhandle. Net present value and total water use over 60 years is used to estimate the value of water for irrigated agriculture in the area. The decline of the Ogallala Aquifer, which is the primary source of irrigation water for the Texas Panhandle, due to excessive extraction rates poses questions about the economic, social and political future of the area.

Economic optimization models for each of the 23 counties in the Texas Panhandle are developed with a goal of maximizing the net income from crop production. Nine crops are selected. Results from the 60-year analysis for the 23 counties indicate a significant transition from irrigated agriculture to dryland farming. Total irrigated crop acres in the study area decrease by approximately 83 percent from 1.79 million acres to 0.30 million acres while total dryland crop acres increase by about 125 percent from 1.20 million acres to 2.69 million acres. Total groundwater use in the study area significantly declines for the planning horizon by 71 percent from 2.16 million ac-ft to 0.63 million ac-ft. The average saturated thickness of the Ogallala Aquifer in the 23 counties shows a 21 percent decline over the planning period.

The results from the model were used to assess the socio-economic impacts of depleting groundwater availability from the Ogallala Aquifer in the region. The models are being used as analytical policy tools to analyze alternative water management strategies and water conservation programs that could be implemented in the area.

Key Words: Economic Optimization, Groundwater Resources, Input Efficiency, Irrigated Agriculture, Southern Ogallala Aquifer, Texas Panhandle.

Introduction: The current state of underground water utilization and availability in the Great Plains is a reflection of the combined result of current economic, social, and political factors. The primary reason why underground water resources in the Great Plains are being used at a rate greater than the natural rate of recharge, is because of the revenues stemming from their current use are greater than the associated cost of extraction. However, underground water use in the Great Plains, given the critical dependence of the regional economy on this resource, is an inter-generational issue that must be evaluated in terms of the sustainability of agricultural activities. For this reason, given the current state of economic, social, and political factors, the sustainability of this resource and its associated economic consequences need to be better understood. Furthermore, many of the current and expected technological advances in agricultural production could have significant impacts on how the future sustainability of underground water resources in the Great Plains is approached.

The economic focus on irrigation from the Ogallala Aquifer and the impact on the region have shifted from development and expansion in the 1950s and 1960s to the implications of the depletion of the aquifer in the 1990s and 2000s (Grubb 1966; Osborn and McCrary 1972; Musick et al 1990; Amosson et al 2001; Colette, Robinson, and Almas 2001). The decline in the water level in the Ogallala Aquifer is an on-going concern. Wells that produced 1000 to 1200 gallons per minute in the 1960s often produced less than 200 gallons per minute in the 1990s. There is only limited recharge of the Ogallala Aquifer in this area. Irrigation water is a fixed supply and excessive pumping results in shortening the economic life of the farming operation and in reducing the returns to the resources held by the farmer. This situation has serious implications not only for the many rural communities on the Texas Panhandle, whose economic base depends on water resources from Ogallala Aquifer, but for the future and continued assurance of the overall competitiveness of the American agricultural sector in the global economy.

Stewart (2003) said that the irrigated area has already decreased from more than 5.9 million acres to about 4.5 million acres. The reduction of total irrigated land will continue for the next several decades as producers switch from irrigation to dryland farming. Therefore, the sustainability of agricultural activities should be central to addressing the declining water table of the aquifer with regard to current political, social and economic factors. It is important not only to measure the potential impact of declining groundwater on agricultural activities by developing regional economic optimization models, but also to develop sustainable irrigation practices to conserve a limited natural resource.

The application of economic principles to the solution of resource management problems and the development of decision aids that incorporate current scientific knowledge and economic theory is essential to the future success of sustainable agricultural production in the area. It is timely and the application of the information and procedures is critical to the survival of agricultural producers faced by the declining water supply associated with the decline in the Ogallala Aquifer. The objectives of this study are to:

1) Develop an economic optimization model for the Texas Panhandle with a goal of maximizing the beneficial use of ground water, and
2) Use the model to evaluate the long-term economic impacts of depleting ground water on the regional economy.

Study Area, Data Collection, and Research Methodology: The Southern Ogallala Central Sub-region includes the 26 counties in the Texas Panhandle, three counties from the Oklahoma

Panhandle and one county from Eastern New Mexico. This study focuses on the 23 counties of the Texas Panhandle that represent the most irrigated agriculture in the area. Figures 1 and 2 illustrate the overall Southern Ogallala Aquifer region and the 26 counties of Texas Panhandle area, respectively.

The harvested crop acres for the model, planted irrigated acres for nine major crops were obtained from the Farm Service Agency (FSA, 2000) and planted dryland acres were obtained from NASS (USDA, 2005). The crops were selected because of their high contribution to the use of groundwater and include alfalfa, cotton, maize, sorghum, soybean, pasture, peanut, wheat, and sorghum forage. Direct and indirect costs include all variable costs except those included as variables in the model such as fertilizers, seed, labor, and energy. These costs are adjusted from projected budget values for specific county crop yield and water coefficient. Crop yields are obtained from the NASS and the Texas Crop and Livestock Budgets (Amosson et al, 2003). Crop prices are calculated using five-year average prices between 1999 and 2003. Input prices such as fertilizer, seed, and labor are also taken from the Texas Crop and Livestock Budgets. Energy prices such as gasoline, diesel, and natural gas are five-year average prices of the years 1999 to 2003 from the Energy Information Administration (EIA, 2005).

Hydrologic data are obtained from two sources: calculated data such as saturated thickness and groundwater volume from Dutton et al. (2001) and the real well data from Driller's Report (Texas Water Development Board, 2005). Total groundwater volume, saturated thickness, and the depth from surface to groundwater bed are used for determining water availability and increases in natural gas requirements from the declining groundwater table estimated by the dynamic programming procedure.

The first step in modeling is to identify the problem and define a system of mathematical expression to address the problem. In this study, the problem is to optimize the return from the use of groundwater from the declining Ogallala Aquifer. In the model, there are decision variables that belong to the decision-making process. For example, a farmer can make a decision on the amount of water applied to his field or on his crop mix (Bernardo et al., 1987). Constraints are functions of the decision variables indicating the interaction of the decision with the availability of resource that affect the obtainment of the good. The objective of the model is to maximize net income from crop production for each county. Net income is defined as the returns to land, risk, management, and the underground water stock. It is calculated as gross returns minus total cost of production, where the latter consists of variable and fixed costs. The variable costs of production include the cost of pumping underground water, investment and maintenance costs associated with the establishment and up keep of irrigation systems/practices, and non-water production costs.

The next step is to build a static-state optimization model for each of the 23 counties for the baseline year, which is the year 2000 in this case. Results from a static model such as groundwater use provide a basis for calculating the water availability level and additional requirements of natural gas during the dynamic programming procedure of the planning horizon. The last step is to calculate the net-present value of a series of net incomes for each county. A three percent discount rate is used to calculate the net prevent value. The model is based on assumptions that limited ground water is optimally allocated among competing agricultural activities, and farmers make rational decisions to maximize their net income when facing scarce resource constraints including land, water, and production inputs. The model maximizes the farmer’s net income from land, management, and the underground water availability for a certain year.

In addition to the production and cost functions, the model requires several other economic and hydrologic parameters. These include: expected crop prices, variable production costs, irrigation labor requirements, water delivery costs, initial pumping depths, initial aquifer saturated thickness, and initial pumping capacity. Crop water coefficients are used as values in the water availability constraint. The model constraints also consist of equations of motion based on county-specific hydrologic parameters. These equations control the dynamic behavior of both saturated thickness and pumping lift. Coefficients in the matrix of the base year model remain constant during the dynamic programming period, except natural gas coefficients. New natural gas requirement are calculated for each irrigated crop each year in order to account for additional pumping lifts as the water table declines. Results of the base model for each county establish the starting point for the dynamic analysis over the 60-year planning horizon. This study analyzes changes in cropland use in response to declining water availability and increasing natural gas requirements associated with the declining groundwater. The pumping cost is calculated from well-known engineering formulas that relate pumping costs to pumping lift, operating system pressure, and the price of energy (Amosson et al., 2001).

Model Specification: In order to estimate the economic life of the aquifer across the region, a dynamic optimization model is developed. The objective of the study is to maximize the net returns from crop production over a 60-year planning period for a given county as a whole.

The objective function is:

$$\text{Max NPV} = \sum_{t=1}^{60} NR_t (1+ r)^{-t} \qquad \text{(i)}$$

where NPV is the net present value of net returns, r is the discount rate, and NR_t is the net revenue at time t. NR_t is defined as:

$$NR_t = \sum_i \sum_k \Theta_{ikt} \{P_i Y_{ikt} [WA_{ikt} ,(WP_{ikt})] - C_{ik} (WP_{ikt} , X_t , ST_t)\} \qquad \text{(ii)}$$

where i represents crop grown, k represents irrigation methods used, Θ_{ikt} is the percentage of crop i produced using method k in time t, P_i is the output price of the crop i, WA_{ikt} water applied per acre, WP_{ikt} water pumped per acre, Y_{ikt} is the per acre yield production function, C_{ik} represents costs per acre, X_t is the pump lift at time t, and ST_t is the saturated thickness of the aquifer at time t. The constraints of the model are:

$$ST_{t+1} = ST_t - [(\Sigma_i \Sigma_k \Theta_{ikt} * WP_{ikt})]A/s, \qquad \text{(iii)}$$

$$X_{t+1} = X_t + [(\Sigma_i \Sigma_k \Theta_{ikt} * WP_{ikt})] A/s, \qquad \text{(iv)}$$

$$GPC_t = (ST_t/IST)^2 * (4.42*WY/AW), \qquad \text{(v)}$$

$$WT_t = \Sigma i\ \Sigma k\ \Theta_{ikt} * WP_{ikt} , \qquad \text{(vi)}$$

$$WT_t \leq GPC_t \qquad \text{(vii)}$$

$$PC_{ikt} = \{[EF(X_t + 2.31*PSI)EP]/EFF\}*WP_{ikt}, \qquad \text{(viii)}$$

$$C_{ikt} = VC_{ik} + PC_{ikt} + HC_{ikt} + MC_k + DP_k + LC_k \qquad \text{(ix)}$$

$$\Sigma_i \Sigma_k \Theta_{ikt} \leq 1 \text{ for all t}, \qquad \text{(x)}$$

$$\Theta_{ikt} \geq (0.9)\ \Theta_{ikt-1} \qquad \text{(xi)}$$

$$\Theta_{ikt} \geq 0. \qquad \text{(xii)}$$

Equation iii updates the saturated thickness variable and equation iv updates the pumping lift variable in the model. 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, and s is the specific yield of the aquifer. GPC in equation v is the gross pumping capacity, IST represents the initial saturated thickness of the aquifer and WY represents the average initial well yield for the county. The factor 4.42 assumes 2000 hours of pumping per season and has the units ac-in/gpm. Equation vi represents the total amount of water pumped per acre, WT_t, is the average water use on all acreage. Constraint vii requires WT_t to be less than or equal to GPC.

Equations viii and ix represent the cost functions in the model. In Equation viii, PC_{ikt} represents the cost of pumping; EF represents the energy use factor for natural gas, EP is the price of natural gas, EFF represents pump efficiency, and 2.31 feet is the height of a column of water that will exert a pressure of 1 pound per square inch. Equation ix represents the cost of production, C_{ikt} in terms of VC_{ik}, is the variable cost of production per acre, HC_{ikt}, the harvest cost per acre, MC_k, the irrigation system maintenance cost per acre, DP_k, the per acre depreciation of the irrigation system per year, and LC_k, the cost of labor per acre for the irrigation system. Equation x limits the sum of all acres of crops i produced by irrigation system k for time period t to be less than or equal to one (1). Equation xi is a constraint placed in the model to limit the annual shift to a 10% change from the previous year's acreage. Equation (xii) is a non-negativity constraint to assure all decision variables in the model have positive values.

Socio-economic models to evaluate the economic impacts on the overall study area and the inter-regional impacts of the alternative scenarios analyzed were developed using the IMpact analysis for PLANing approach (Minnesota IMPLAN Group, 2001). The (regionally aggregated) output of the optimization models was used as input into the socio-economic models, along with other socioeconomic parameters required by the IMPLAN model such as the social accounting matrix. The socio-economic models were constructed so that relevant information with respect to the structural and transitional changes likely to take place over time is derived including changes such as: overall and specific commodity economic activity levels, sectoral employment opportunities, and changes in income.

Results and Discussion: The expected aggregate changes in cropping pattern in the entire region for irrigated crops mainly maize and wheat show acreage reductions of about 81 and 99 percent, respectively. The proportion of maize in the total harvested crop acres drops from 22 percent to four percent. Irrigated wheat almost disappeared by the end of the period despite its initial large portion in total crop acres. However, acres for major dryland crops such as dryland cotton, and dryland wheat increase significantly by approximately 214 and 212 percent, respectively. The proportion of dryland wheat significantly increases from about 26 percent to 82 percent for the same period. With respect to minor crops, all crops except alfalfa exhibit a reduction in their production acreage. Alfalfa increases from 2,271 to 159,283 acres. Alfalfa accounts for only 0.04 percent of cropland in 2000 but represents about five percent of total crop acres in 2060.

As Figure 3 shows, the initial average saturated thickness of the Ogallala Aquifer in the Texas Panhandle was 139.29 feet. With unconstrained water usage, the average saturated thickness declines at an average of 0.46% per year to a level of 105.75 feet, or 75.92% of the original level during the 60 years. These changes in saturated thickness are a result of the crop mix changing from irrigated crops to dryland crops as the amount of water available for irrigation is reduced. The percentage of the total crop acres planted in irrigated crops falls from about 60% to almost 11% under the unrestricted scenario as shown in Figure 4. The projected water use over the period of 60 years for the entire region is presented in Figure 5. The gradual trend downward is a result of the crop mix changing each year due to the increased pumping costs associated with declines in the aquifer level from one year to the next.

With no restriction on water use (Table 1), irrigated maize planted drops from 22.4% of the total acreage in the region to 2.33% in year 60. This is a drop from 670,634 acres to only 69,790 acres. Under the same scenario, irrigated soybean drops from 54,713 acres to 116 acres or from 1.83% to nearly 0%. Irrigated sorghum dropped from 170,233 to 310 acres, or from 5.69% of total acreage to 0.01%, and dryland sorghum drops from 372,338 acres, or 12.44%, to 110,406 acres, or 3.69%. Irrigated wheat falls from 19.51%, which is 19.51 aces, to 0.09%, or 2,815 acres. However, most of this shift is from these crops to dryland wheat, which starts at 26.12% of total crop acreage, or 781,784 acres, to 85.32%, which is 2,553,897 acres.

For the entire region, the net present value (NPV) of net returns over a 60-year period in the baseline scenario was $1,436 million with irrigation and $515 million under no irrigation scenario. The value of irrigated agriculture for the region was projected as the difference, $921 million. This clearly shows that any policy aimed at reducing irrigation will have a significant economic impact on the region, with some counties experiencing severe losses in revenues. This is a major concern that must be addressed when considering policy alternatives, because these losses, when combined with the lost resource demand, will have a significant impact on rural economies that rely on agriculture.

Production levels for crops are greatly affected by changes in crop distribution over the planning period. With respect to changes in inputs, seeds for all the crops except wheat and alfalfa decrease for the period. Consumption levels of both nitrogen and phosphorous fertilizers are reduced because of the transfer of cropland from fertilizer-intensive crops such as maize to less intensive crops like dryland wheat. For energy consumption, there is no big change in consumption of either diesel or gasoline but natural gas use declines due to the reduction in irrigation. The economic optimization model can be used to analyze alternative policy scenarios such as change in natural gas prices, water pumping restriction and incentives to producers for management practices to be used for water conservation.

Socio-economic impact can be divided into three categories: direct effects, indirect effects and induced effects. The direct effects are the impacts for the expenditures and/or production values specified as direct final demand changes. Indirect effects are the impacts caused by the iteration of industries purchasing from industries resulting from direct final demand changes. Induced effects are the impacts on all local industries caused by the expenditures of new household income generated by the direct and indirect effects of direct final demand changes. Total effects are the sum of the direct, indirect, and induced effects. The socio-economic model generated projections of macroeconomic measures such as employment, regional income, and tax revenues. The baseline model results, presented in Table 2, indicate that the total effects of “do nothing” option could be $929 million loss of industry output, 19000 job loss in employment sector and $485 million loss in value added activities. This indicates that irrigated agriculture in the region contributes significantly to the regional economy.

Summary and Implications: Total irrigated crop acres in the study area decrease by approximately 83 percent while total dryland crop acres increase by about 125 percent. Total groundwater use in the area significantly declines over the planning horizon by 71 percent from 2.16 million ac-ft to 0.63 million ac-ft. The trends and relative changes indicated by this study seem appropriate. The model shows the reduction of total irrigated land for the planning period as producers switch from irrigation to dryland farming. Comparing net present value of an optimization model under different policy scenarios can be used to calculate opportunity costs for conserving natural resources. For example, the difference in NPV, for two alternatives might represent the amount of payment required by farmers as compensation for adopting a policy that restricts the use of their resources.

However, care should be taken in interpreting the magnitude of the individual values as true cardinal relationships. The usefulness of the model can be improved by expanding the definition of crop land to include crop rotations that include fallow such as wheat-fallow or wheat-sorghum-fallow rotations, and adjusting the yields to reflect the production practices.

The optimization models applied to agriculture often yield "unrealistic" results. The optimal solutions of the model often diverge from farmers' observed behavior. A common example is that some time model produces a corner solution where all land is planted to a single crop (implying this crop is the most profitable alternative given the model parameters), while farmers tend to diversify their acreage portfolio across several crops.

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Table 1. Percent Changes in Total Acres Planted in Major Crops, Selected Years

Year	Irrigated Corn	Irrigated Soybean	Irrigated Sorghum	Dryland Sorghum	Irrigated Wheat	Dryland Wheat
2000	22.40%	1.83%	5.69%	12.44%	19.51%	26.12%
2010	16.96%	0.76%	2.01%	6.77%	13.58%	49.92%
2020	14.07%	0.26%	0.70%	4.22%	6.36%	66.47%
2030	11.57%	0.09%	0.24%	3.45%	2.22%	76.57%
2040	8.87%	0.03%	0.09%	3.32%	0.75%	81.74%
2050	5.15%	0.01%	0.03%	3.51%	0.27%	84.48%
2060	2.33%	0.00%	0.01%	3.69%	0.09%	85.32%

Table 2. Socio-economic Impact Analysis of Baseline Senario

	Industry Output	Employment	Value Added
Direct	-513,332,480	-12,739	-238,420,564
Indirect	-308,269,684	-5,140	-180,912,278
Induced	-107,269,417	-1,257	-66,167,393
Total Effects	**-928,871,581**	**-19,137**	**-485,500,235**

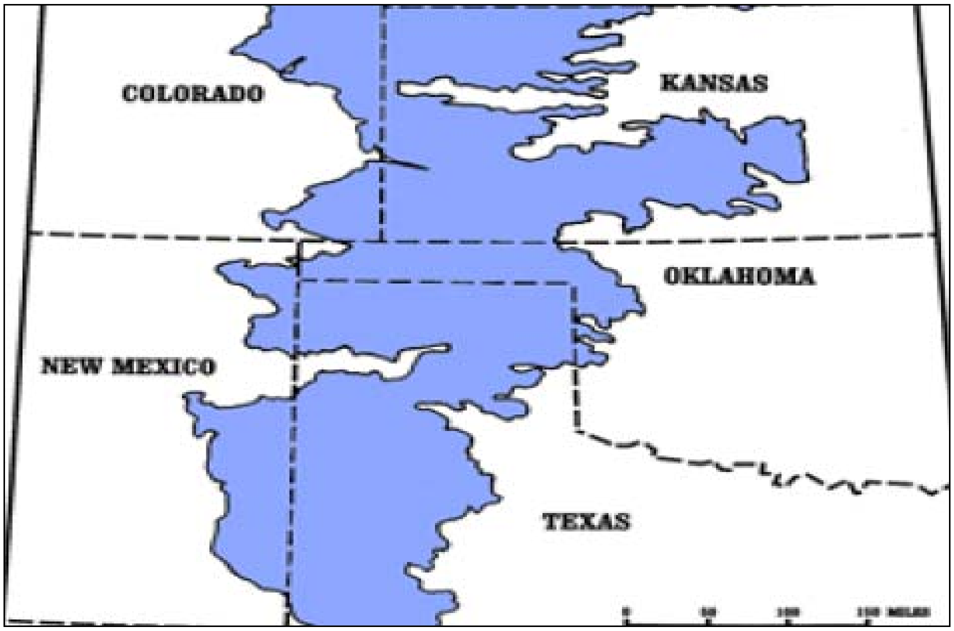

Figure 1. Southern Ogallala Aquifer Region (The Kerr Center, 2005)

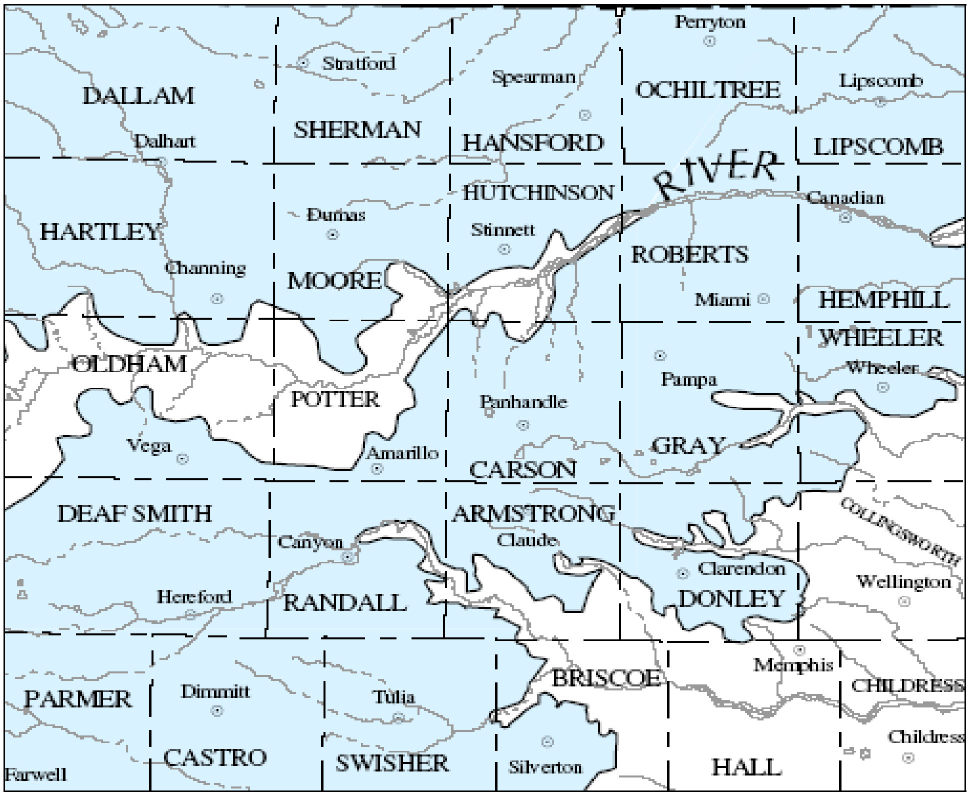

Figure 2. Twenty-six Counties of the Texas Panhandle (USDI-USGS, 2003)

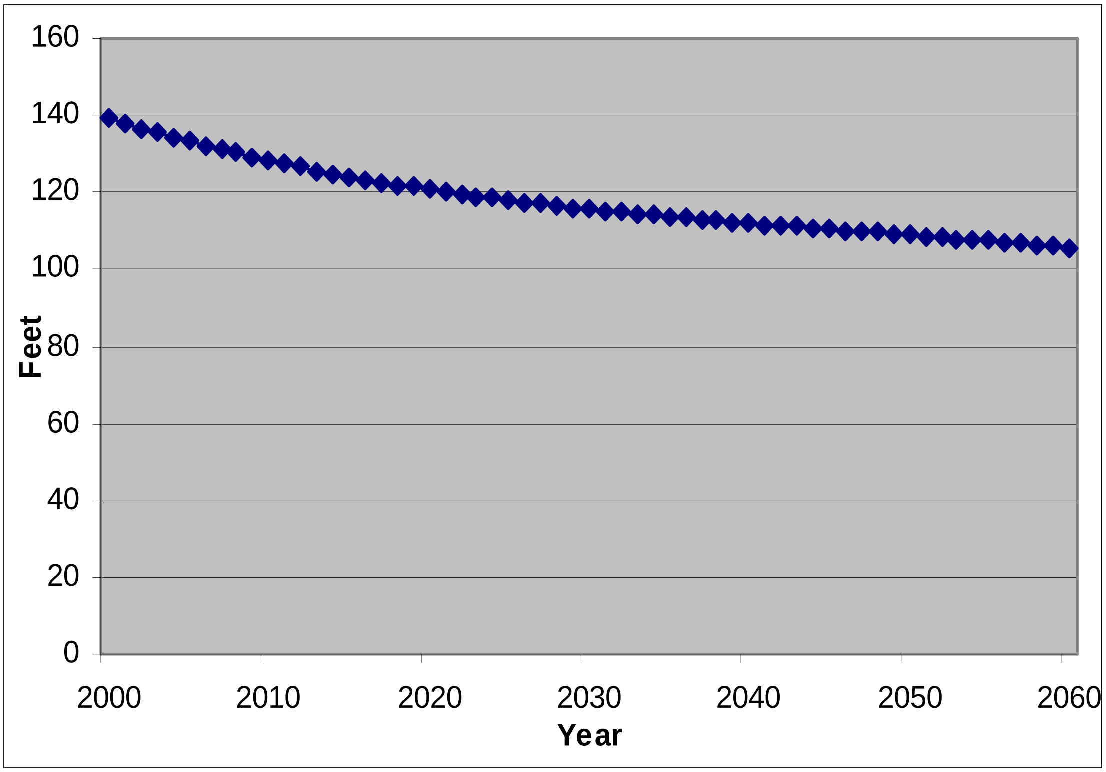

Figure 3. Projected Changes in Saturated Thickness of Ogallala Aquifer in Texas Panhandle

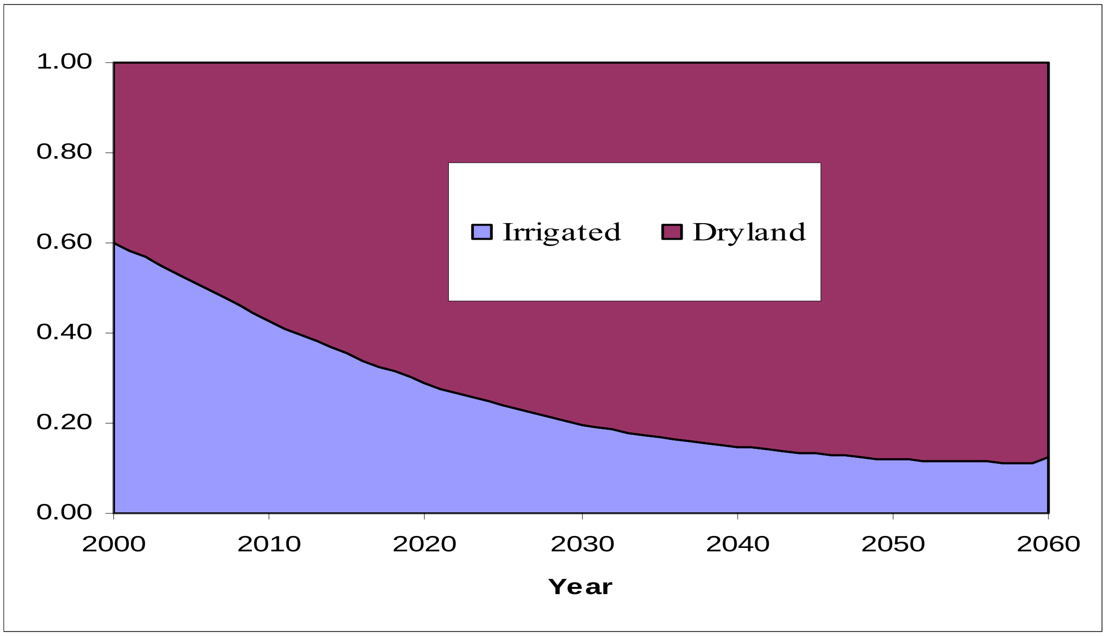

Figure 4. Projected Changes in Irrigated vs Dryland Acres in Texas Panhandle

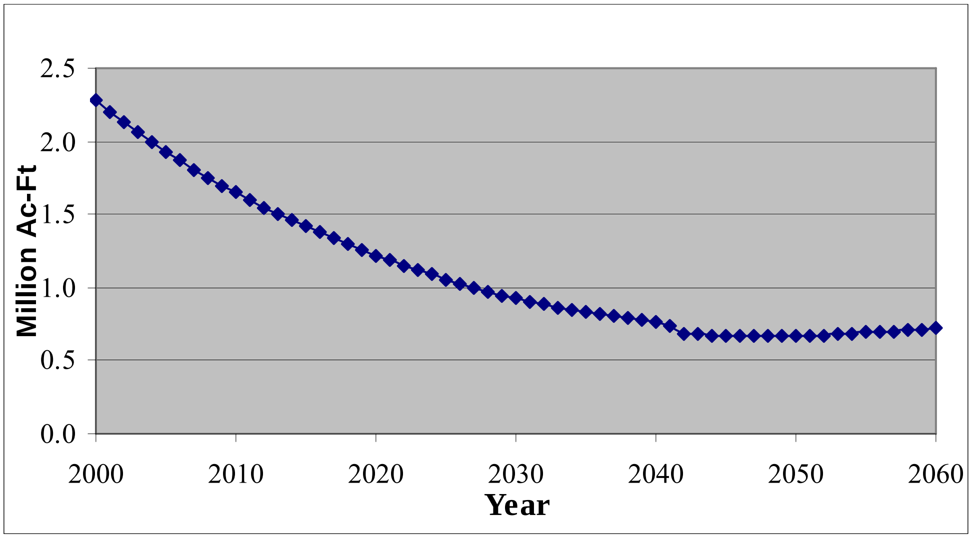

Figure 5. Projected Groundwater Use for Irrigation in Texas Panhandle