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Multi-year water allocation: an economic approach towards future planning and management of declining groundwater resources in the Texas Panhandle

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Abstract: Heavy withdrawals from the Ogallala Aquifer, the most dependable source of groundwater in the Texas Panhandle, create an impending need for implementing water conservation policies. This study evaluates the policy option of multi-year water allocation coupled with water-use restriction in Regional Water Planning Area-Region A of Texas, over a 60-year planning horizon for 4 study counties, namely Dallam, Sherman, Moore and Hartley. Dallam County is studied as a representative county and results compared with other study counties. For the unconstrained baseline scenario over 60 years, the counties of study show a decline in saturated thickness that recommends the incorporation of water-use restriction alternatives at different rates. Increasing restrictions rates led to decline in water use per acre as well as total annual water use. Such restrictions, if mandated by the water conservation districts, will result in individual irrigators bearing the cost of water savings in the form of reduction in net present value per acre. The decline in net present value may have implications to the regional economy, and therefore, it is crucial to analyze the socio-economic effects of implementing such a policy alternative and analyze the feasibility in the light of legislative and political scenarios.

Keywords: dynamic optimization, irrigation, multi-year allocation, Ogallala Aquifer

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Terms used in paper

Short name or acronym	Descriptive name
GAMS	General Algebraic Modeling Systems
LEPA	low energy precision application
NPV	net present value

INTRODUCTION

The economy of the Texas High Plains is driven by agriculture, and irrigation that utilizes groundwater resources plays a pivotal role in the development of cropping systems and sustaining the growth and productivity of the farming community in the area. The most important and dependable source of groundwater for irrigation purposes in this region is the Ogallala Aquifer, which overlies parts of 8 states: Texas, New Mexico, Oklahoma, Colorado, Kansas, Nebraska, South Dakota, and Wyoming (Alley et al. 1999). However, water table levels in the aquifer have been declining in certain locations over the years, more specifically in the southern and central region of the aquifer. This rate of decline is accelerated by the fact that recharge, when compared to the rate of depletion, is minuscule (Birkenfeld 2003). In 1990, the Ogallala Aquifer in the 8-state area of the Great Plains contained approximately 3½ billion acre-feet of water, of which Texas had about 12% of the water in storage or approximately 417 million acre-feet of water (Guru and Horne 2000). A recent estimate of the volume of water in the 8-state Great Plains area was less than 3 billion acre-feet (Tuholske 2008). Such changes in the groundwater resource supply will most likely have a significantly negative impact on the agricultural economy of the Texas High Plains in the near future.

The Texas law of water rights for groundwater has a complex structural framework that can be accounted for by inclusion of certain features of the Spanish law such as absolute ownership of groundwater by landowners (Wishart 2011), along with the incorporation of the traditional English common law (Handbook of Texas Online 2009). The rule of capture is the guiding principle behind percolating groundwater (percolating below the surface of the earth (Tex. Water Code §36.001(5) (Texas Constitution and Statues 2011)), and is sometimes referred to as the "law of the biggest pump." This principle has been derived from the English common law that was adopted in the year 1904 by the Texas Supreme Court in a historical ruling, which has been recorded as Houston and Central Texas Railway vs. East (East Ruling) (TWDB 2004). Under this rule the owner of the overlying land can pump and use the water with few restrictions, whatever the impact on adjacent landowners or more distant water users. The rule of capture has been maintained as the case law for groundwater in the State of Texas, ever since the East ruling and has been modified with regard to groundwater management in different regions. Therefore, it is crucial to understand various policy options that could be incorporated in the current water rights system for a particular area with an objective of conserving water for future use. Several studies have been undertaken in this regard. Wheeler et al. (2008) evaluated the impacts of short-term and long-term water-rights buyout policies. The results of the study suggested that the long-term buyouts were more economically efficient than short-term buyouts. Johnson et al. (2009) studied the impacts and economic effects of implementing groundwater policies on the Ogallala Aquifer in the Southern High Plains of Texas and concluded that a policy that restricts the quantity of groundwater pumped conserved more water over the 50-year planning horizon than implementation of a water-use fee, but at a higher cost. These studies provide an insight into scope of further research regarding water policy implementation in the study area with a long-term objective of water conservation in the aquifer.

Water allocation over multiple years may be of interest to policy-makers and the state legislature with an objective of extending the economic life of the Ogallala Aquifer in the High Plains of Texas and maintaining the viability of a regional economy that critically depends on agriculture. The North Plains Groundwater Conservation District, in its groundwater management plan for the years 2008–2018, set a maximum allowable production limit of 2 acre-feet per acre, per annum on water-rights tracts not to exceed 1,600 acres. This was done with an objective to limit groundwater withdrawal amounts based on an allowable production limitation and a contiguous water-right acre limitation (NPGCD 2008). Although the rule of capture remains in effect, local groundwater conservation district rules supersede. Therefore, any allocation system advocated in the State of Texas will need to be adjusted accordingly by the groundwater districts in their respective areas. In the above context, a "district" is defined as an authority formulated to regulate the spacing of water wells, the production from water wells, or both, as defined in the Texas Water Code §36.001(1) (Texas Constitution and Statues 2011).

A water allocation system over multiple years will potentially reduce inefficient use of water during the allocated period by allowing for water stock (allocation) to accumulate for the judicious users, which could be rolled over into the next allocation period at an appropriate rate of the unused stock. This system will also pave the way for producers to manage irrigation needs of their crops in a planned manner with better utilization of available water than previously used. The goal of the multi-year allocation policy is to allow an equitable distribution of a limited resource like water and ensure its availability in the future, given the excessive groundwater mining and associated decline in water levels from a limited water source for the area.

The objective of this study is to analyze and evaluate the impacts of multi-year water allocation as a policy alternative for optimizing groundwater use from the Ogallala Aquifer in the Northern High Plains of Texas. In this study, county-specific models were developed with an objective of maximizing net returns from the existing agricultural systems over a planning horizon of 60 years. A comparative analysis was conducted to evaluate the impacts of allocating the use of groundwater resources over a 5-year period under 3 different scenarios (15%, 30%, and 45% water-use restriction from baseline year-1 water use) when compared to a hypothetical baseline scenario, which assumes current water use with no restriction. The results of the study were evaluated for parameters such as change in saturated thickness, pump lift, water application per acre and also for changes in crop mix, over the planning horizon under the restriction scenarios. In addition, net present value per acre was estimated for the baseline as well as the alternative scenarios to compare the feasibility and economic effects of policy implementation along with the restriction scenarios.

STUDY AREA

Declining levels of water in the aquifer have led to significant discussions among regulating authorities and water-law governing bodies, creating an impending need to realize the importance of the complexity of water laws affecting usage of groundwater in the Texas High Plains. The concept of estimated usable life in terms of aquifer yield, and the basin yield, can be instrumental in realizing the importance of the study area. Freeze and Cherry (1979) define aquifer yield as the maximum rate of withdrawal that can be sustained by an aquifer without causing an unacceptable decline in the hydraulic head in the aquifer. This indicates that the usable lifetime of an aquifer pumped at the aquifer yield is eternity, given acceptable consequences. However, due to continued withdrawals and the unconfined nature of an aquifer like the Ogallala, the estimated usable lifetime is better represented by the basin yield, which is the quantity of water available from a stream at a given point over a specified duration of time (Reddy 2004). The primary focus of this research concentrates on the northwest region of the Texas High Plains, more specifically the counties of Dallam, Sherman, Moore, and Hartley. In a study conducted by the Center for Geospatial Technology at Texas Tech University, the counties of study showed substantial change in amount of water storage underlying the county over a study period of 15 years from 1990 to 2004 (Barbato and Mulligan 2009). The percent change for individual counties was: Dallam, -22.7; Sherman, -14.2; Moore, -11.5; and Hartley, -8.1 (Barbato and Mulligan 2009). Wheeler et al. (2006) studied the impacts of water conservation policies that limit drawdown of the Ogallala Aquifer and concluded that in the High Plains of Texas, water conservation policies that focus on counties that deplete the aquifer to less than 30 feet of saturated thickness with respect to the usable lifetime over a 60-year period were most likely to benefit from the focus of water conservation. This emphasizes the fact that counties with lower estimated usable life and high water use should be studied extensively for measures of water conservation. Dallam County has a substantial area that falls in the estimated usable life of less than 15 years. Sherman and Moore counties follow the trend with an estimated usable life ranging from 31 to 100 years. Hartley County, however, shows a mixed scenario where certain locations of the county experienced high depletion and, on the other hand, other locations experienced a rise in water table. Figure 1 outlines the counties of study in the Texas High Plains, which are located in the Regional Water Planning Area–Region A.

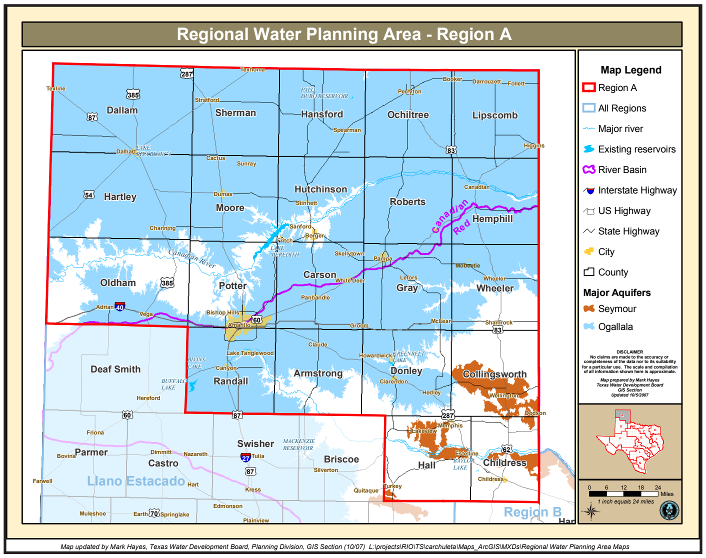

Figure 1. Counties of study in Region A – Regional Water Planning Area. Source: Texas Water Development Board 2007.

DATA SOURCES AND METHODOLOGY

Several steps were necessary to analyze the economic impacts of the multi-year water allocation policy coupled with restriction scenarios when compared to the baseline scenario of no restriction on water use. The study utilized the General Algebraic Modeling Systems (GAMS), which is a mathematical programming and optimization modeling software. For the purpose of this research, GAMS was specifically employed for developing non-linear optimization models for each county using specific parameters. The model for this specific study is a non-linear dynamic model with the incorporation of crop production functions for individual crops in the study area. These crops are corn, grain sorghum, cotton, and wheat. An approach that utilized non-linear dynamic programming in combination with GAMS (Brooke et al. 1998) was used in this research study to facilitate multiple runs of the model. First, hydrologic data were collected for the study counties for saturated thickness, pumping lift, hydraulic conductivity, and recharge rate, which were needed to calculate the water withdrawal on an annual basis for irrigation. Specific data were collected for 5-year average planted acreages of cotton, corn, grain sorghum, wheat, and fallow land from the Farm Service Agency for the years 2005 to 2009 (FSA 2009). Crop acreages under conventional furrow, low energy precision application (LEPA), and dryland were calculated utilizing the ratio of acreages under different irrigation systems from the Texas Water Development Board Survey of Irrigation (TWDB 2001). Operating costs were collected for specific crops of study, including fertilizer, herbicide, seed, insecticide, fuel, irrigation technology maintenance, irrigation, labor, and harvesting costs for the year 2009 (Amosson et al. 2009).

The developed models estimated the optimal water requirements for irrigation and the resulting net returns from crop production for major crops in the 4 counties of study over a 60-year planning horizon. A 3% discount rate was used to calculate the net present value for the 60-year period for each of the 4 counties.

Hydrologic data

Saturated thickness and pump lift by county calculations were based on data for the year 2008 from the Texas Tech University Center for Geospatial Technology website (TTU CGT 2010). Saturated thickness was calculated by subtracting the depth to water from the depth of the well. Pump lift was calculated as the depth from the ground surface to the water level. Recharge rate used in the model on a county-wide basis was obtained from the Panhandle Water Planning Group report on adjustments of parameters to improve calibration of models of the Ogallala Aquifer (Dutton 2004). An average estimated specific yield of 0.155 was used for the entire study area (Ryder 1996). Initial acres served per well and maximum allowable withdrawal were calculated from the Texas Water Development Board Survey of Irrigation (TWDB 2001). It was assumed that, as saturated thickness values for counties decrease, the well yield in gallons per minute also declined. As an example, for counties with saturated thickness above 80 feet, a well yield of 1,000 gallons per minute was assumed for modeling purpose. The well yield values assumed for modeling purpose were guided by the assumption that the maximum allowable annual withdrawal for each county in acre-feet would require a minimum average well yield for satisfying the water demand. The average hydraulic conductivity used in the model for Ogallala Aquifer in Texas is estimated to be 65 feet per day (Ryder 1996). Initial acres served per well were calculated by dividing the groundwater irrigated acres by the approximate number of wells in each county. All estimated and calculated hydrologic parameters are summarized in Table 1.

Production functions

The production function parameters by crop for each county were calculated by using field data obtained through personal communication with farmers in the counties of study (Personal communication from Leon New, Extension Agricultural Engineer, Texas AgriLife Extension Service, Amarillo, Texas. 2010). The production techniques and timing of cultural practices were held constant for irrigated crops with only the irrigation water amounts changing. Maximum and minimum water applications for each crop were also incorporated in the model. The minimum water application levels

Table 1. Hydrologic parameters for counties of the study area.

County	Pump lift (feet)	Saturated thickness (feet)	Well yield (gallons per minute)	Acres per well
Dallam	371	128	1,000	134
Sherman	340	182	1,000	114
Moore	260	162	1,000	107
Hartley	420	153	1.000	148

used in the model were 14, 7, 7, and 6 inches per acre for corn, cotton, sorghum, and wheat, respectively, while the maximum water application level for the above crops was capped at 36 inches per acre. Application efficiency for the LEPA and furrow irrigation systems were established as constants and the production functions were allowed to adjust with the application efficiencies in the functional form specifications for equations in the model.

Response functions were estimated from the field data using the quadratic functional form with yield per acre as the dependent variable and irrigation water applied as the independent variable. The coefficients (β_1, β_2) were estimated setting the intercept to zero or the respective dryland yield of the crop, achieved without irrigation as reported for the county. The crop-water production function thus developed established the relationship between crop yield and applied irrigation. With this function, producers and policy-makers can understand and evaluate irrigation water requirements in order to achieve targeted production or, conversely, estimate the most feasible and best-fit crop production functions for fixed or limited volumes of irrigation water. The established equation was represented as follows:

(1) $$Y = \beta_0 + \beta_1 X - \beta_2 X^2$$

where Y represents the yield and X represents water application rate.

Commodity prices and harvest costs

Prices and harvest costs for corn, cotton, sorghum, and wheat were obtained from the budgets available for District 1 from Texas AgriLife Extension Service (Amosson et al. 2009) for the year 2009 and are presented in Table 2. It is important to mention that a surge in prices of commodities like corn with considerable acreage in the study area may have significant impacts on future production and expansion, as long as it is economically viable to pump water for irrigated production.

Model specification

This study was conducted with an objective of finding the optimal combination on individual county basis, using models to maximize net returns from production of crops over a time horizon of 60 years.

The objective function is defined as:

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

where NPV represents the net present value of net returns; r represents the discount rate; and NR_t represents net revenue at time t. The bounds of summation for the net revenue are from 1 to 60 years. NR_t is defined as:

(3) $$NR_t = \Sigma_i \Sigma_k \Omega_{ikt}\{ P_i Y_{ikt} [WA_{ikt}, (WP_{ikt})] - C_{ik} (WP_{ikt}, X_t, ST_t)\}$$

where i represents crops grown; k represents irrigation systems used; Ω_{ikt} represents the percentage of crop i produced using irrigation system k in time t, P_i represents the output price of crop i, WA_{ikt} and WP_{ikt} represent irrigation water application per acre and water pumped per acre, respectively. Y_{ikt} represents the per acre yield production function, C_{ikt} represents the costs per acre, X_t represents pump lift at time t, ST_t represents the saturated thickness of the aquifer at time t. The bounds of summation are 1 to 5 and 1 to 3 for i and k respectively.

Table 2. Harvest cost and commodity prices in the study area for the year 2009.

	Units	Cotton	Corn	Sorghum	Wheat
Yield unit		pounds/acre	bushels/acre	cwt/ac	bushels/acre
Harvest cost	dollar/unit	0.1	0.42	0.88	0.67
Commodity price	dollar/unit	0.56	4.75	8.1	5.78

The main constraints of the model are:

(4) $ST_{t+1} = ST_t - [(\Sigma_i \Sigma_k \Omega_{ikt} * WP_{ikt}) - ARR]\ PIA/SY,$

(5) $X_{t+1} = X_t + [(\Sigma_i \Sigma_k \Omega_{ikt} * WP_{ikt}) - ARR]\ PIA/SY,$

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

(7) $WT_t = \Sigma_i \Sigma_k \Omega_{ikt} * WP_{ikt},$

(8) $WT_t \leq GPC_t$

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

(10) $C_{ikt} = VPC_{ik} + PC_{ikt} + HC_{ikt} + MC_k + DP_k + LC_k$

(11) $\Sigma_i \Sigma_k \Omega_{ikt} \leq 1$ for all t,

(12) $\Omega_{ikt} \geq (2/3)\ \Omega_{ik(t-1)},$

(13) $\Omega_{ikt} \geq 0$

Equations (4) and (5) update the 2 state variables, saturated thickness and pumping lift, ST_t and X_t respectively where *ARR* represents the annual recharge rate in feet, *PIA* represents 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 *SY* represents the specific yield of the aquifer. In equation (6), *GPC* represents gross pumping capacity, *IST* represents the initial saturated thickness of the aquifer in year one of the planning horizon, i.e. 2010, and *WY* represents the average initial well yield for the county in year one. Constraints (7) and (8) are the water application and water pumping capacity constraints, respectively. Equation (7) represents the total amount of water pumped per acre, WT_t, as the sum of water pumped on each crop. Constraint (8) requires WT_t to be less than or equal to *GPC*. Equations (9) and (10) represent the cost functions in the model. In Equation (9), PC_{ikt} represents the cost of pumping, *EF* represents the energy use factor for electricity, *EP* is the price of energy, *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 (10) expresses the cost of production, C_{ikt}, in terms of VPC_{ik}, 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 (11) limits the fractional sum of all acres of crops *i* produced by irrigation systems *k* for time period *t* to be less than or equal to one. Equation (12) is a constraint placed in the model to limit the annual shift to a 33.3% change from the previous year's acreage. This was done with an objective of constraining the model from predicting rapid shifts towards dryland cropping. Equation (13) is a non-negativity constraint to assure all decision variables in the model take on positive values. The model works on the objective of profit maximization and finds the optimal by maximizing the 60-year NPV typically called the social planners solution.

RESULTS

Results were analyzed for the optimal levels of saturated thickness, annual net revenue per acre, pump lift, water applied per cropland acre, cost of pumping, and net present value of net returns per acre by county. These were derived using the non-linear dynamic optimization model for the baseline scenario of a 5-year water allocation policy with no restriction on water use and the 3 alternative scenarios of a 5-year water allocation policy coupled with water-use restriction rates of 15%, 30%, and 45% respectively.

Results for Dallam County

The results for the baseline model and 3 water-use restriction scenarios for a multi-year allocation over 5 years will be discussed and analyzed in this section for Dallam County. Dallam County was selected as the representative county because the entire county overlies the aquifer, has a diverse crop mix, and has crop acreages in both irrigated and dryland. The total irrigated acreage within this county is 220,695 acres, of which 1,858 acres utilize furrow irrigation systems and 218,837 acres utilize sprinkler irrigation, with LEPA as the major irrigation system. The dryland crop acreage for this county is 60,621 acres. The Ogallala Aquifer underlies the total county area of 963,004 acres. Corn is the predominant crop grown in this county, with 100% of the acreage under sprinkler system, which is 126,330 acres. Winter wheat is another important crop of this county, with 1,696 acres under furrow irrigation system and 83,122 acres using LEPA systems. There is substantial dryland acreage of winter wheat in this area, which is 42,777 acres. Sorghum is also grown in both irrigated and dryland conditions and the irrigated furrow, LEPA and dry acreages are 162 acres, 7,939 acres, and 10,509 acres, respectively. Cotton is a minor crop in the area, grown only under LEPA irrigation systems and has acreage of 1,446 acres. The fallow land within this county is 22,005 acres.

In the baseline scenario, which assumes current water use and absence of a water-use constraint, saturated thickness declined from 128 feet to 42 feet during the 60-year period. The net revenue per acre for the county decreased from $213.6 in year 1 to $48.7 by year 60. The net present value per acre of cultivated land for the county is $4,404.70 for 60 years. Average water applied per cropland acre decreased from 16.62 inches to 3.51 inches over 60 years and the nominal pump cost increased from $8.40 per acre inch to $10.20 per acre inch during the planning horizon of 60 years.

Comparison of water-use restriction scenarios for Dallam County

In this section, results of specific water-use restriction rates for the allocation policy are compared to the baseline.

Scenario A (15% reduction in water use from Baseline Year-1)

This scenario placed a constraint on the annual water use, with a 15% reduction from Baseline Year-1 water use and the allocation period assumed was 5 years, as in the baseline scenario. The results indicated that saturated thickness declined from 128 feet to 43.05 feet during the 60-year period, which is 1% less than the baseline scenario. The net revenue per acre for the county decreased from $174.20 in year 1 to $54.90 by year 60. The net present value of productivity per acre of cultivated land for the county is $4,209.20 for 60 years, which is 4% less than the baseline. Average water applied per cropland acre decreased from 14.13 inches to 3.73 inches in the 60th year, which was 15% less than that applied in the 60th year of the baseline scenario. The nominal pump cost increased from $8.40 per acre inch to $10.20 per acre inch during the planning horizon of 60 years. The total annual water use for the entire county decreased from 348,532 acre-feet in year 1 to 92,035 acre-feet by year 60, when compared to the baseline scenario of annual water use from 410,038 acre-feet in year 1 to 86,584 acre-feet by year 60.

Scenario B (30% reduction in water use from Baseline Year-1)

This scenario placed a constraint on the annual water use, with a 30% reduction from Baseline Year-1 water use and the allocation period assumed was 5 years, as in the baseline scenario. The results indicated that saturated thickness declined from 128 feet to 54 feet during the 60-year period, which is 14% less than the baseline scenario. The net revenue per acre for the county decreased from $120.80 in year 1 to $14.40 by year 60. The net present value per acre of cultivated land for the county is $2,318.50, which is 47% less than the baseline. Average water applied per cropland acre decreased from 11.64 inches to 5.86 inches in the 60th year, which was 30% less than that applied in the 60th year of the baseline scenario. The nominal pump cost increased from $8.40 per acre inch to $10.00 per acre inch during the planning horizon of 60 years. The total annual water use for the entire county decreased from 287,027 acre-feet in year 1 to 144,645 acre-feet by year 60, when compared to the baseline scenario of annual water use from 410,038 acre-feet in year 1 to 86,584 acre-feet by year 60.

Scenario C (45% reduction in water use from Baseline Year-1)

This scenario placed a constraint on the annual water use, with a 45% reduction from Baseline Year-1 water use and the allocation period assumed was 5 years, as in the baseline scenario. The results indicated that saturated thickness declined from 128 feet to 57 feet during the 60-year period, which is 17% less than the baseline scenario. The net revenue per acre for the county decreased from $53.40 in year 1 to $9.40 by year 60. The net present value per acre of cultivated land for the county is $1,083.50, which is 75% less than the baseline. It is observed that both net present value and water applied per cropland acre decrease successively with increasing water-use restriction rates. Therefore, individual irrigators will bear the cost of water savings in the form of reduction in net present value per acre, if such a restriction is mandated by the water conservation district. It is also important to realize the depreciation in the value of land when converted from irrigated to dryland production. Irrigated cropland in the study area with good water has a value of $2,200 to $2,800 per acre and dry cropland values range from $350 to $500 per acre in 2009 dollars (TAMU REC 2009). Therefore, the irrigator is faced with various options and has to decide on the most profitable alternative accompanying the cost of water conservation. Average water applied per cropland acre decreased from 9.14 inches to 6.41 inches in the 60th year, which was 61% less than that applied in the 60th year of the baseline scenario and the nominal pump cost increased from $8.40 per acre inch to $9.90 per acre inch during the planning horizon of 60 years. The total annual water use for the entire county decreased from 225,521 acre-feet in year 1 to 158,090 acre-feet by year 60, when compared to the baseline scenario of annual water use from 410,038 acre-feet in year 1 to 86,584 acre-feet by year 60. The comparisons for parameters of saturated thickness, average water applied per cropland acre, and net returns per acre, under the 3 restriction scenarios, and baseline for Dallam county are provided in Figure 2.

General observations about regional results

As discussed previously in the unconstrained baseline scenario, all the 4 counties in the region (Dallam, Sherman, Moore, and Hartley) showed a decrease in the saturated thickness over the planning horizon in addition to reduction in net revenue per acre and also in water applied per cropland acre. These counties are among the highest water-use counties of the Panhandle region with low estimated usable life for the Ogallala Aquifer, with the exception of Hartley, which shows a rise in water table in certain parts (Barbato and Mulligan 2009).

Results of the baseline scenario and policy alternatives with

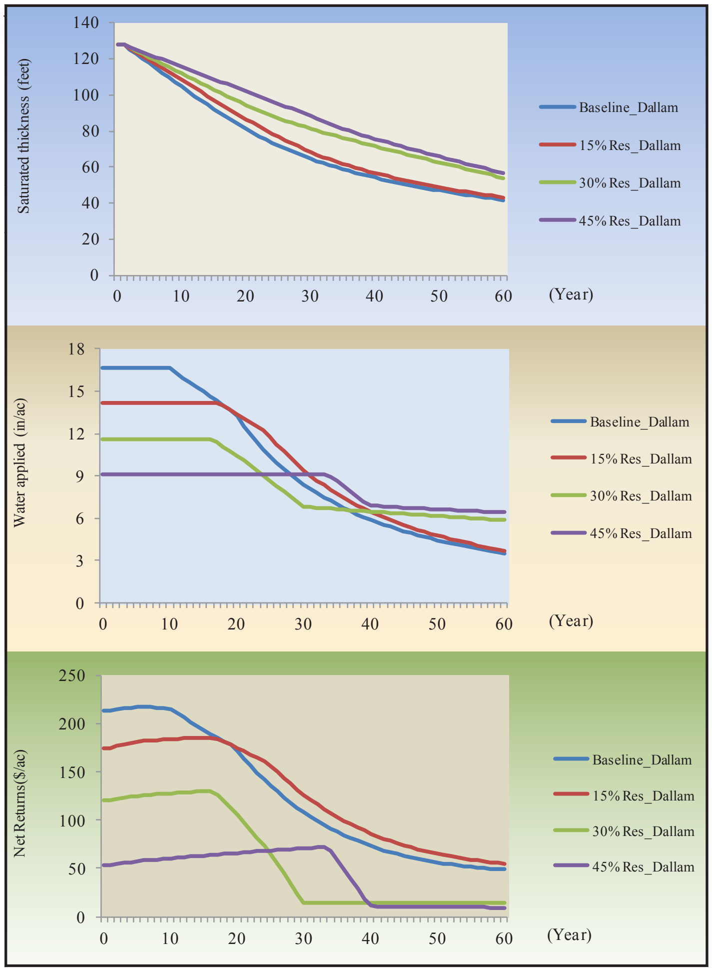

Figure 2. Changes in saturated thickness, water applied per acre, and net returns per acre for Dallam County under different scenarios.

of the counties over the planning horizon was comparatively less in the restriction scenarios when compared to the baseline. The water applied per cropland acre decreased in the baseline scenario within a range of 76.02% to 78.90% decrease in the counties from year 1 to year 60. This decrease was more significant with increasing water-use restriction rates and led to a change in cropping patterns in the study area.

Dryland acreage of sorghum increased substantially and irrigated sorghum, wheat and cotton acreages witnessed a decline during the planning horizon. The acreage for sprinkler irrigated corn shows a very slow decline rate in all the scenarios for each county, due to the high acreage of corn and its importance as the major livestock feed in the area. Irrigated acreage for all the major crops under furrow irrigation systems went out of production by the 20th year and showed a shift towards the more efficient sprinkler irrigation systems. A graphical description to understand the movement in crop-mix over the planning horizon is provided in Figure 3. Dallam County's baseline scenario is used as an illustration to depict these changes.

The results also showed a decrease in the net present value and net revenue per acre under all the scenarios for each county of study during the planning horizon. The net revenue per acre showed a decline in the range of 71.20% to 89.02% in the study counties under the baseline scenario. This decline became more evident with progressive rates of water-use restriction. Detailed results for the counties of study for the above parameters are presented in Table 3.

In order to validate the results of the model, a trend in actual crop acreages over the years 2005–2008 were studied utilizing the most recent data for the study area. It was observed that in the years of observation, the total irrigated corn acreage for the 4 counties, continuously increased from 37% in year 2005 to 41% in year 2008, which is also depicted by the results of the model for all the 4 counties of study until water became limiting at a point in time in the planning horizon. Again, from the observations, it was found that the total irrigated sorghum acreage for the 4 counties increased from the year 2005 to the year 2006 but slightly decreased in the years 2007 and 2008. Dryland sorghum showed an increase in the same trend as irrigated sorghum, and again decreased slightly during the years 2007 and 2008. Irrigated wheat increased continuously throughout the years of observation from 25% to 30% and dryland wheat decreased in the year 2006 but again rose in the year 2007. Irrigated cotton saw a moderate decline throughout the years of observation. It should be noted that the results of the model showed an increase in the dryland acreage of sorghum throughout the planning horizon, and this increase in the actual observations of the crop acreages for the study area was interrupted by an increase in irrigated wheat acreage, due to the high commodity prices for wheat crop in the year 2008.

The results of the model show a consistent trend with the actual crop acreages; however, it is important to realize that the

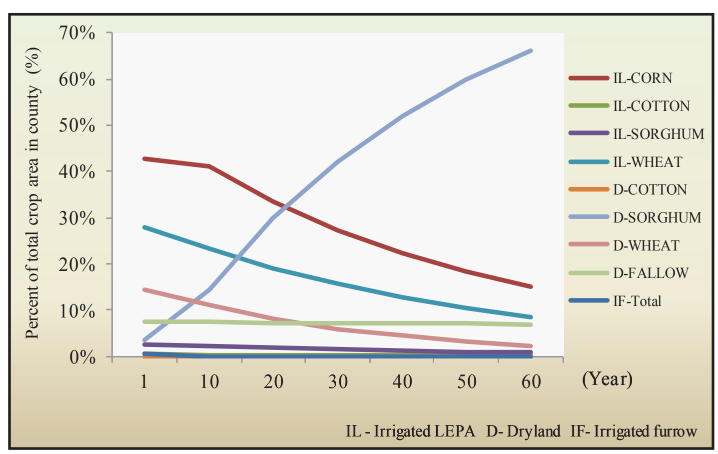

Figure 3. Shift in crop mix for Dallam County under the baseline scenario.

Table 3. Results for the counties of study — Baseline and 3 alternative scenarios.

Dallam	**Baseline**		**15% Redc.**		**30% Redc.**		**45% Redc.**	
	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60
Saturated thickness (feet)	128	41.76	128	43.05	128	53.97	128	56.42
Change from baseline				3%		29%		35%
Water applied (inch/acre)	16.62	3.51	14.13	3.73	11.64	5.86	9.14	6.41
Change from baseline			-15%	6%	-30%	67%	-45%	83%
Net returns (dollar/acre)	213.67	48.74	174.25	54.98	120.84	14.47	53.45	9.48
Change from baseline			-18%	13%	-43%	-70%	-75%	-81%
Sherman	**Baseline**		**15% Redc.**		**30% Redc.**		**45% Redc.**	
	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60
Saturated thickness (feet)	182	51.69	182	53.86	182	58.69	182	70.59
Change from baseline				4%		14%		37%
Water applied (inch/acre)	13.89	3.13	12.83	3.4	10.56	4.03	8.3	5.83
Change from baseline			-8%	9%	-24%	29%	-40%	86%
Net returns (dollar/acre)	173.12	40.09	162.31	47.35	125.12	60.68	72.82	14.61
Change from baseline			-6%	18%	-28%	51%	-58%	-64%
Moore	**Baseline**		**15% Redc.**		**30% Redc.**		**45% Redc.**	
	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60
Saturated thickness (feet)	162	42.65	162	48.94	162	51.93	162	56.24
Change from baseline				15%		22%		32%
Water applied (inch/acre)	11.93	2.86	11.28	3.77	9.29	4.24	7.3	4.98
Change from baseline			-5%	32%	-22%	48%	-39%	74%
Net returns (dollar/acre)	170.15	18.65	162.77	14.51	128.03	12.65	79.42	9.84
Change from baseline			-4%	-22%	-25%	-32%	-53%	-47%
Hartley	**Baseline**		**15% Redc.**		**30% Redc.**		**45% Redc.**	
	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60	Year 1	Year 60
Saturated thickness (feet)	153	60.55	153	62.11	153	70.56	153	77.11
Change from baseline				3%		17%		27%
Water applied (inch/acre)	18.69	4.68	15.89	4.93	13.08	6.35	10.28	7.59
Change from baseline			-15%	5%	-30%	36%	-45%	62%
Net returns (dollar/acre)	226.34	65.35	186.69	70.54	131.26	7.28	60.05	3.14
Change from baseline			-18%	8%	-42%	-89%	-73%	-95%

models are dynamic optimization models, which are guided by the profitability and production costs of commodities in the base year. In this study, crop budgets for the year 2009 were utilized in the models for calculating the net revenue and the net present value for each county on a per acre basis and did not consider changes in commodity prices or input costs over time (in 2009 dollars). Therefore, the most optimal and profitable combinations of crop mix for a given county are depicted by the model, given the current water use and its future availability over the planning horizon.

CONCLUSIONS

The results from this study indicate that in all 4 counties, there was a greater reduction in net present value per acre with increasing rates of restriction scenarios when compared to the baseline. Under the unconstrained baseline scenario, the counties of study show a decline in saturated thickness over a 60-year planning horizon that recommends the incorporation of water-use restriction alternatives at different rates. As shown by the results, the reduction in net present value per acre becomes higher with increase in water-use restriction rates for all the counties in the study area, and therefore it is important to analyze the socio-economic effects of the same. This study faced limitations with regard to the availability of data sets for several parameters across similar time frames. Therefore, it is important to mention that although these were the most recent datasets pertaining to individual parameters, the economic results obtained through the model may be impacted by the input parameters, if used across different years. While considering water conservation policy alternatives for the Ogallala Aquifer, it is crucial to realize the set of legislative norms that govern groundwater use in a particular region or state. The rule of capture, still being the primary law governing underground water use in the State of Texas, limits the incorporation of water policy alternatives unless suitable relaxations or changes are made as deemed necessary by groundwater conservation districts in the region. Therefore, it is of vital importance that studies be carried out that address these issues and analyze the suitability and feasibility of a policy like multi-year allocation in the light of legislative and political scenarios.

Another interesting possibility in the research direction of this policy could be the incorporation of a moving 5-year constraint in the model that will permit 'carry-over' of unused water and also take into consideration stochastic weather conditions and change in recharge rate. This will allow the researchers to achieve the possibility of finding suitable optimization scenarios to overcome production risk in a multi-year allocation model.

REFERENCES

Alley WM, Reilly TE, Franke OL. 1999. Sustainability of ground-water resources. Denver (Colorado): United States Geological Survey. USGS Circular 1186.

Amosson SH, Almas LK, Bretz FE, Jones D, Warminski P, Planchon J. 2009. Texas High Plains, 2010 Texas crop and livestock enterprise budgets. Amarillo (Texas): Texas AgriLife Extension Service, Texas A&M University System. B-1241 (C1).

Barbato L, Mulligan K. 2009. Atlas of the Ogallala Aquifer Program [Internet]. Lubbock (Texas): Texas Tech Center for Geospatial Technology; [cited 2009 October 20]. Available from: http://gis.ttu.edu/ogallalaatlas/

Birkenfeld D. 2003. Reclaiming water as a commons. Southwest Chronicle: a publication of Southwest Collection/Special Collections Library, Texas Tech University. 4:2.

Brooke A, Kendrick D, Meerdus A, Raman R, Rosenthal RE. 1998. GAMS: a user's guide. Washington, D.C.: GAMS Development Corporation.

Dutton A. 2004. Adjustments of parameters to improve calibration of the Og-n model of the Ogallala Aquifer, Panhandle Water Planning Area. Austin (Texas): The University of Texas at Austin, Bureau of Economic Geology. Report prepared for Freese and Nichols, Inc., and Panhandle Water Planning Group.

[FSA] Farm Service Agency. 2009. Crop reporting records.

Freeze RA, Cherry JA. 1979. Groundwater. 1st edition. Englewood Cliff (New Jersey): Prentice-Hall. 305 p.

Guru MV, Horne JE. 2000. The Ogallala Aquifer [Internet]. Poteau (Oklahoma): The Kerr Center for Sustainable Agriculture; [cited 2009 November 25]. Available from: www.kerrcenter.com/publications/ogallala_aquifer.pdf

Handbook of Texas Online. 2009. Water Law [Internet]. Denton (Texas): Texas State Historical Association; [cited 2009 November 25]. Available from: http://www.tshaonline.org/handbook/online/articles/WW/gyw1.html

Johnson J, Johnson PN, Segarra E, Willis D. 2009. Water conservation policy alternatives for the Ogallala Aquifer in Texas. Water Policy 11(5):537-552.

[NPGCD] North Plains Groundwater Conservation District. 2008. Groundwater management plan. [cited 2009 November 25]; Available from: http://www.twdb.state.tx.us/groundwater/docs/GCD/npgcd/npgcd_mgmt_plan2008.pdf

Ryder PD. 1996. High Plains Aquifer. Groundwater atlas of the United States, Oklahoma, Texas [Internet]. Reston (Virginia): U.S. Geological Survey; [cited 2009 November 25]. Ha 730-E. Available from: http://pubs.usgs.gov/ha/ha730/ch_e/E-text5.html

[TAMU REC[Texas A&M University Real Estate Center. 2009. Rural Land Values [Internet]; [cited 2009 November 25]. Available from: http://recenter.tamu.edu.

Texas Constitution and Statues. 2011. Water code [Internet]. [cited 2013 April 20]. Available from: http://www.statutes.legis.state.tx.us/Docs/WA/htm/WA.36.htm

[TTU CGT] Texas Tech University Center for Geospatial Technology. 2010. Texas County Water Information [Internet]. [cited 2009 November 25]. Available from: http://www.gis.ttu.edu/OgallalaAquiferMaps/TXCounties.aspx

[TWDB] Texas Water Development Board. 2001. Survey of Irrigation in Texas [Internet]. Austin (Texas): Texas Water

Development Board; [cited 2009 November 25]. Report 347. Available from: http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/R347.pdf.

[TWDB] Texas Water Development Board. 2004. 100 years of rule of capture: from East to groundwater management [Internet]. Austin (Texas): Texas Water Development Board; [cited 2009 November 25]. Report 361. Available from: http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R361/R361.pdf

[TWDB] Texas Water Development Board. 2007. TWDB maps [Internet]. Austin (Texas): Texas Water Development Board; [cited 2009 November 25]. Available from: www.twdb.state.tx.us/mapping/maps.asp

Tuholske J. 2008. Trusting the public trust: application of the Public Trust Doctrine to groundwater resources. Vermont Journal of Environmental Law. 9(2):189-238.

Wheeler E, Segarra E, Johnson P, Johnson J, Willis D. 2006. Aquifer depletion and the cost of water conservation: the Southern High Plains of Texas case. International Association of Agricultural Economists 2006 Annual Meeting, August 12-18, 2006, Queensland, Australia. number 25410.

Wheeler E, Golden B, Johnson J, Peterson J. 2008. Economic efficiency of short-term versus long-term water rights buyouts. Journal of Agricultural and Applied Economics. Southern Agricultural Economics Association 40(2):493-501.

Wishart DJ. 2011. Spanish water law, Encyclopedia of the Great Plains [Internet]. [cited 2012 April 30] Available from: http://plainshumanities.unl.edu/encyclopedia/doc/egp.wat.030

Reddy PJR. 2004. A textbook of hydrology. Daryaganj (New Delhi): Laxmi Publications Pvt Limited. 331 p.