The Impact of Spatial Heterogeneity in Land Use Practices and Aquifer Characteristics on Groundwater Conservation Policy Cost

David B. Willis

Associate Professor, Department of Applied Economics and Statistics, Clemson University,
Clemson, SC 29634-0313, willis9@clemson.edu

Jeff Stovall

Professional Engineer, Project Manager Water Resources Department, Espey Consultants, Inc.
Po Box 31870, Amarillo, Texas 79120-1870

Jeffrey Johnson

Assistant Professor, Department of Agricultural and Applied Economics, Texas Tech University,
Lubbock, Texas 79409-2132

Ken Rainwater

Professor, Department of Civil Engineering, Director Texas Tech University Water Resources
Center, Texas Tech University, Lubbock, Texas79409-2132

Lucia S. Barbato

Center for Geospatial Technology Texas Tech University, Lubbock, Texas 79409-2132

Kevin Mulligan

Center for Geospatial Technology Texas Tech University, Lubbock, Texas 79409-2132

Ernest B. Fish

Professor, Department of Natural Resources Management, Texas Tech University, Lubbock,
Texas 79409-2132

Selected Paper prepared for presentation at the Southern Agricultural Economics Association 43rd Annual Meetings, Corpus Christi, Texas, February, 5-8, 2011
.

The Impact of Spatial Heterogeneity in Land Use Practices and Aquifer Characteristics on Groundwater Conservation Policy Cost

Abstract

Estimation of agricultural policy cost for a given level of groundwater conservation requires the establishment of an accurate baseline condition. This is especially critical when benefits and cost of a conservation program are estimated relative to the status quo policy or baseline situation. An inaccurate baseline estimate will lead to poor estimates of potential water conservation savings and/or agricultural policy cost. Over a 60-year planning horizon per acre net present value is as much as 29.8% higher for a study area when aquifer characteristics are modeled as homogenous and set to their average area value than when the heterogeneity in aquifer characteristics is explicitly modeled.

Introduction

Differences in modeling scale between economic and hydrologic models often require the aggregation of hydrologic parameters and economic variables to a level that may not sufficiently control for important spatial variability differences in land use characteristics and/or hydrologic parameters and result in inaccurate estimates of expected future water use and conservation savings for alternative water conservation policies. Previously, Das and Willis (2004) linked a spatially disaggregated hydrologic model of the Southern Ogallala Aquifer to a dynamic economic model characteristic of agricultural production in the Texas High Plains (THP) and found that the failure to accurately account for spatial heterogeneity in aquifer characteristics, overstated both expected baseline agricultural net returns, and cumulative water use over a 50 year planning horizon. This overstatement resulted in an over estimate of conservation cost and potential cumulative water savings when conservation policy cost and water saving were measured relative to the inaccurate baseline condition. This research extends this prior policy modeling effort by controlling for the effects of spatial heterogeneity in land cover, irrigation technology, and aquifer characteristics when estimating the agricultural policy cost and conservation effectiveness of five alternative groundwater conservation measures.

For each study region, the revised detailed water policy model is used to evaluate the benefit and cost of five potential water conservation policies. The five policies consist of two policies that directly restrict groundwater use, and three policies that indirectly restrict groundwater use by decreasing the number of irrigated acres from the current initial year baseline level. The first water restriction policies considered is implementation of a water use restriction that annually reduces groundwater withdrawals by 1% beginning from the initial year baseline level over the 60-year planning horizon. Under this policy, the maximum quantity of water that can be withdrawn in year 60 is 40% of the initial year withdrawal level. The second water restriction policy considered simulates the net effect of an annual 1% reduction in groundwater withdrawals in combination with an assumption that biotechnology advances will increase crop yields by 0.5% annually over the planning horizon. The three indirect land use policies considered can be are a temporary irrigated land retirement policy and two permanent irrigated land retirement policies. The temporary water right retirement policy assumes that 2% of the initial year irrigated acreage is converted to dryland production each year over a five year period for a total conversion of 10% after five years. This temporarily idled acreage is then allowed to phase back into irrigated production over a five-year period beginning in year sixteen if the economic incentive is sufficiently strong. The two variants of the permanent land retirement policy consist of a permanent reduction in initial baseline irrigated acreage that is phased in over five years and assumes 2% of initial year irrigated acreage is annually idled for a to achieve a10% reduction in initial year irrigated acreage. This acreage irrigated acreage remains idle for 15 years before being allowed to be converted to dryland production. In subsequent discussion, this policy is referred to as the PERM LAND A policy. The second variant of the permanent irrigated reduction policy is labeled PERM LAND B policy and is similar to the PERM LAND A policy in that it also assumes that 2% of irrigated initial year irrigated acreage is annually removed from irrigated production over a five year period, beginning in year two of the optimization. However, the PERM LAND B policy differs from the

PERM Land A policy because idled irrigated acreage can immediately be converted to dryland production instead of have to be kept idle for 15 years as required by the PERM LAND A policy.

Objective of the Study

Our primary objective is to compare simulated economic and hydrologic output generated by a dynamic economic water planning model to similar output generated from an integrated water policy model that links the dynamic economic model to a spatially and temporally disaggregated hydrologic model. Non-integrated conventional economic water policy models are generally constructed under the assumption that the hydrologic relations existing within a county, region, or sub-region are homogenous for all areas within the defined area when considerable variability exits. We illustrate that even a well-designed dynamic economic model has severe limitations when estimating expected future groundwater supply and demand conditions when the simulated forecasts are derived from a water policy/planning model that is not coupled to a valid hydrologic model that controls for the spatial variability (heterogeneity) of an aquifer's hydrologic characteristics. The cost-effectiveness of a proposed water conservation policy is normally measured against the status quo baseline policy when estimating the net economic benefit and/or quantity of water conserved by the potential conservation policy. If the baseline condition is inaccurately estimated, the subsequent estimates of water conservation policy cost and level of water conservation savings realized will be inaccurately estimated relative to the baseline condition.

Study Area

As illustrated in Figure 1, the 42,000 square mile Southern Ogallala Aquifer comprises the southern-most third of the Ogallala Aquifer system. The Canadian River valley and the

Prairie Dog Fork of the Red River valley divide the Southern High Plains from the Central High Plains region of the Ogallala Aquifer (Stovall 2001). Eighty-five percent of the Southern Ogallala aquifer is located within Texas and the remaining 15% resides in eastern New Mexico (HPUWCD undated). There is very little hydraulic connectivity between the Southern Ogallala aquifer and the Central Ogallala aquifer (Stovall 2009). The Southern Ogallala aquifer is now being mined as an exhaustible resource, and cumulative agricultural withdrawals over the last 50 years have decreased stored reserves to approximately 50 percent of their 1940 storage level (Ogallala Commons 2004). Guru and Horne (2000) have estimated that annual withdrawals from the Southern Ogallala Aquifer because are at least 10 times greater than the natural recharge rate.

Figure 2 identifies the 19 heavy agricultural groundwater water using counties in the THP. The 19 counties account for 97 % of all Texas agricultural groundwater withdrawals from the Southern Ogallala Aquifer. In an effort to control for the heterogeneity of land use practices and aquifer characteristics for three relatively homogenous 400 square mile study regions were identified. The location of each 400 square mile THP study area is identified in Figure 3. The study area regions are labeled Castro-Lamb, Hale Floyd, and Gaines-Terry in recognition of the two counties that respectively contain most of the surface area in each respective study area. Even though average land use practices and aquifer characteristics are significantly different between each selected study areas, these individual regions were selected for analysis because a collected GIS data indicated that the land use practices and aquifer characteristics in each region were relatively homogenous relative to degree of variability observed in most other areas of the THP.

Table 1 reports the initial crop mix for each study area. Over 82% of the Castro-Lamb area crops are grown under irrigation whereas slightly less than 56% of the Hale-Floyd crops are grown under irrigation. Currently, slightly more than 72% of Gaines-Terry crop acreage is grown under irrigation. In addition to having more acreage under irrigation than the Hale-Floyd study area, both the Castro-Lamb and Gaines-Terry study areas have a greater proportion of their irrigated acreage in high-valued water intensive crops. As shown in Table 2, given the increased scarcity of water in the THP in combination with the high valued crops grown in the Castro-Lamb and Gaines-Terry study areas over 90% of the irrigated acreage in these two areas produced under 95% efficient LEPA systems. However, within the Hale-Floyd study area nearly 25% of irrigated acreage is produced using furrow irrigation technology, and is most likely attributable to the lower valued, less water intensive, crops grown within the area.

Despite our efforts to identify three areas within the THP that are relatively homogeneous within their boundaries regarding land use practices and aquifer characteristics, considerable spatial variation still exists aquifer with regard to aquifer characteristic each study site. A detailed GIS data analysis generated the data summarized in Table 3 (Barbato et al., 2008). The coefficient of variation statistic reveals that the pump lift (depth to the water table) and saturated thickness aquifer characteristics are most variable for the Gaines-Terry study area and least variable for the Castro-Lamb study area. Thus a modeling approach that establishes a dynamic baseline water use time derived under the assumption that aquifer characteristics are homogenous would most likely have the greatest error in the Gaines Terry study area, because the distribution of pump lift variability has differential impacts on groundwater acquisition costs and the variability in saturated thickness will cause some areas of the aquifer to go dry earlier than expected under the homogeneity assumption.

METHODS AND PROCEEDURES

Model Overview

An updated and revised version of the Texas High Plains (THP) water policy model originally developed by Das and Willis (2004) is used to investigate the impact that spatial variability in land use practices, irrigation technology and aquifer characteristics have on the expected groundwater use over a sixty-year planning horizon for three 400 square mile study areas in the THP. Stovall's (2009) hydrologic model calibrated for the Southern Ogallala Aquifer is the hydrologic model used in this analysis. The widely-used MODFLOW ground water simulation program (McDonald and Harbaugh 1988) was the software program used to construct the ground water model. Stovall's model divides the land overlying the aquifer into a rectangular grid comprised of one-mile square cells. The Southern Ogallala Aquifer grid consists of 246 rows and 184 columns, or 45,264 grid cells. Each grid cell contains parameter values for hydraulic conductivity, specific yield, recharge rate, initial saturated thickness, and the initial (current) volume of water withdrawn from each cell in the baseline calibration period. Given user-provided parameter values for the aquifer's physical characteristics, MODFLOW uses a finite numerical difference equation procedure in combination with water budgets that account for recharge, withdrawals, and net lateral inflows to monitor saturated thickness and water table elevation through time (McDonald and Harbaugh 1988). As shown in Figure 2, Stovall's hydrologic model is calibrated for the entire Southern Ogallala Aquifer which spans 32

Texas counties in the Texas Panhandle and eight counties in northeastern New Mexico. The Southern Ogallala Aquifer grid provides the means to link agricultural land use practices contained in the economic model to the hydrologic model at a one square mile resolution level.

The economic model estimates the optimal agricultural ground water extraction time path that maximizes the present value of agricultural net returns over a 60-year planning horizon. The Crop Production and Management Model (Gerik et al. 2003) was used to develop nonlinear crop production functions to describe crop yield response to applied water for given soil types, irrigation systems, and average weather conditions. Region- specific irrigated crop production functions are estimated for the five dominant irrigated crops grown in the THP. These five crops are corn, cotton, grain sorghum, peanuts, and wheat and collectively account for 97 percent of agricultural crop water use within the THP. In total, two hundred seventy technology and region specific irrigated production functions were estimated. To provide a dryland alternative to irrigation, region-specific average dryland crop yields were estimated for 27 specific production regions in the THP using NASS data conditional on weather conditions and representative crop management techniques. Additional region-specific data input into the dynamic economic model include initial saturated thickness, initial average pump lift, initial average well yield, initial average acres served per well, and initial number of irrigated and dryland acres by crop. The variable costs for dryland crop production and the additional costs for irrigation are taken from enterprise budgets for Texas Extension District 2 (Texas Agricultural Extension Service Budgets 2006-2009).

The initial distribution of crops and irrigation systems in each of the three identified study areas was compiled using a GIS data set for compiled for each study region (Fish, 2008). Energy data included an energy use factor for electricity of 0.164 KWH/feet of lift/acre-inch, system operating pressure of 16.5 pounds per square inch, and pump engine efficiency of 50%. The KWH cost of energy is $0.102, the average price for the 2004 to 2008. Other costs include the per acre cost of each irrigation system, irrigation system depreciation, annual per acre irrigation system labor, maintenance, and depreciation cost. Average crop price was calculated using NASS price data for the years 2006-2009 as reported by the Texas Agricultural Statistics Service. A 3 percent real discount rate is used to convert the per acre annual returns over the 60 year planning horizon to a per acre net present value. By linking the economic models to the hydrologic model, the integrated modeling approach is able to maintain the spatial variability in hydrologic response to agricultural ground water stresses. A complete discussion of the THP water policy model is found in Das (2004).

Economic Model Specification

The optimization model maximizes the net present value of annual per acre returns to land, management, groundwater stock, risk, and investment over a specified planning horizon. Annual net income is expressed as:

$$(1) \qquad NI_t = \sum_c \sum_i \Theta_{cit}\{([P_c + LDP_c]*Y_{cit}(WP_{cit})) - TVC_{cit}(WP_{cit}, L_t, ST_t)\},$$

where c represents the crop grown, i represents the type of irrigation system (center pivot irrigated, furrow irrigated or non-irrigated), and t represents the time period, Θ_{cit} represents the percentage of crop c produced with irrigation system i in period t, P_c represents the price of crop c, LDP_c is the average loan deficiency payment per unit of crop c produced, Y_{cit} represents the yield per acre of crop c produced with irrigation system i in period t, WP_{cit} represents the amount of water pumped in cubic meters to irrigate crop *c* through irrigation system *i* in period *t*, TVC_{cit} represents the total variable cost of production per acre of crop *c* produced with irrigation system *i* in period *t*, L_t represents the pump lift in meters in time *t*, ST_t represents the saturated thickness of the aquifer in time *t*, and NI_t represents the net income over variable cost in time *t*. Yield (Y_{cit}) was calculated using the previously discussed crop production functions. The objective function that is maximized over the 60-year planning horizon is as shown in Equation 2:

$$(2) \qquad Max\ PVNI = \sum_{t}^{60} NI_t * (1+r)^{-t}$$

And can be expressed equivalently as shown in Equation 3 by substituting equation 1 into Equation 2.

$$(3)$$
$$Max\ PVNI = \sum_{c}\sum_{i}\sum_{t}\Theta_{cit} * \{([P_c + LDP_c] * Y_{cit}(WP_{cit})) - TVC_{cit}(WP_{cit}, L_t, ST_t)\} * (1+r)^{-t}$$

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

Equation 3 is maximized subject to the following set of constraints:

$$(4) \qquad ST_{t+1} = ST_t - [(\sum \sum \Theta_{cit} * WP_{cit}) - R_t]/S$$

$$(5) \qquad L_{t+1} = L_t + [(\sum \sum \Theta_{cit} * WP_{cit}) - R_t]/S$$

$$(6) \qquad GPC_t = 4.42 * (IWY / AW) * (ST_t / IST_t)^2$$

$$(7) \qquad PER\ ACRE\ WATER\ USE_t = \sum_{c}\sum_{i}\Theta_{cit} * WP_{cit}$$

(8) $$PER\ ACRE\ WATER\ USE_t \le GPC_t$$

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

(10) $$TVC_{cit} = NIRVC_{ci} + IRRENERGYCOST_{cit} + HC_{cit} + MC_i + DP_i + LC_i$$

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

(12) $$\sum_c \sum_i \Theta_{cit} \le \mathit{Initial\ Irrigated\ Percentage}\ \ \forall\ i = \mathit{center\ pivot\ or\ \ furrow}$$

(13) $$\Theta_{cit} \ \ge 0.666 * \Theta_{cit-1}$$

(14) $$\Theta_{cit} \ \ge \ 0$$

(15) $$TotalWaterUse_t = PerAcreWaterUse_t * TotalAcres$$

Equations 4 and 5 are equations of motion for the two state variables of saturated thickness (ST_t) and pumping lift (L_t), where R_t is the annual recharge rate in acre inches per acre of aquifer, S represents the specific yield of the aquifer, and WP_{cit} is the acre inch volume of water withdrawn from the aquifer in period t and applied to crop *c* using irrigation technology *i* in period *t*. Data for initial year saturated thickness and pumplift was taken from a detailed GIS data base compiled by Barbato et al (2008).

Equations 6, 7, and 8 express the relationship between the volume of water pumped and the amount of water available. Equation 6 estimates the maximum volume of water that can be applied per irrigated acre in each time period. Per acre gross pumping capacity in period *t* (GPC_t), is a function of initial saturated thickness *(IST)*, average initial well yield for a county *(WY)*, and average number of wells per irrigated acre within the county *(AW)* (Harman, 1966;

Terrell, 1998; and Texas Water Development Board, 2001). The unit of measure associated with the factor 4.42 is acre-inches per gallon per minute (ac-in/gpm) and the value was developed assuming a well pumps 2000 hours in the growing season.[1] Equation 7 calculates the volume of water pumped per irrigate acre ($PER\ ACRE\ WATER\ USE_t$) as the sum of water pumped on each crop under each technology weighted by the percent to total crop acreage produced under the crop and irrigation technology combination. Equation 8 is a constraint that assures the per acre volume of water pumped ($PER\ ACRE\ WATER\ USE_t$) is less than or equal to the per acre amount of water available for pumping (GPC_t). A limitation of this specification of the pumping constraint it that it inherently assumes that land-use practices and aquifer characteristics are homogenous within a region.

Equation 9 calculates the per acre irrigation energy cost of pumping and applying irrigation water to crop *c* produced using irrigation system *i* in period *t* ($IRENERGYCOST_{\mathrm{cit}}$), where *EF* represents the energy use factor for electricity, L_t is well lift in period *t*, PSI_i is irrigation system operating pressure in pounds per square inch (zero for furrow irrigation), *EP* represents energy price per unit of electricity, *EFF* represents pump engine efficiency, and the factor 2.31 is the height in feet of a column of water that will exert a pressure of 1 pound per square inch (Terrell, 1998). Equation 10 calculates the total variable cost per acre (TVC_{cit}) for crop *c* produced by irrigation system *i* in period *t.* Per acre TVC_{cit} is calculated as the sum of $NIRVC_{ci}$ non irrigation related variable cost for crop *c* under irrigation technology *i,* plus HC_{cit} the per acre harvest cost for crop *c* under irrigation system *i*, plus MC_i the annual per acre

---

[1] [(2000 hours) * (60 minutes/hour) * (43,560 cubic feet/acre-foot)] /[(7.48 gallons/cubic foot) * (12 inches/foot)] = 4.42 acre-inches/gallon per minute.

maintenance cost for the irrigation system *i*, plus DP_i the annual per acre depreciation cost for irrigation system *i*, and LC_i the per acre irrigation labor cost for irrigation system *i*.

Equation 11 limits the sum of the percentage of area for all crops *c* produced by all irrigation systems *i* for each period *t* to be less than or equal to 1. Equation 12 ensures that the percentage of acres irrigated does not increase above the initial percentage at the beginning of the planning horizon in each county. Without this restriction and given the time value of money the optimization procedure found it more profitable to increase irrigated acreage in the short-run. However, increasing irrigation acreage in the short-run is inconsistent with the fact that irrigated acreage has been decreasing over time in the study regions.

Equation 13 limits the annual reduction in crop acreage under a specific irrigation technology to be no more than 33.33% of the previous year's acreage. This limit on the rate of transition between crop enterprises controls the rate at which the model allows producers to switch from one enterprise to another in order to replicate an agronomic orderly transition between crop enterprises. Equation 14 ensures that the values of the decision variables, Θ_{cit} , the amount of acreage devoted to a given crop and irrigation technology are non-negative.

Equation 15 is an accounting equation calculates the total volume ground water withdrawals in a given specified region at each time period t. Total ground water use in each period t is calculated as the average quantity of groundwater withdrawn and applied per acre of cropland multiplied by the total quantity of cropped acres in the initial time period. Total cropped acreage in a county is the sum of irrigated and non-irrigated acres in the initial period. As the quantity of water applied to an irrigated crop decreases and or the percent of land in dryland crop production increases the average quantity of water applied per cropped acre decreases. Though not included in the above model specification, irrigated peanut acreage was restricted to be no more than one-third irrigated acreage at any point in time. This restriction ensured that peanuts, which are exclusively grown under irrigation, are rotated with another crop four years in six to control for potential agronomic disease problems.

Aquifer Model

The first step toward overcoming the limitations of conventional economic water policy models that treat aquifer characteristics as homogenous within a study region is to link a detailed hydrologic model to the dynamic economic model to more accurately capture the relationship between land use economic activity and aquifer status. Coupling the hydrologic equations of motion governing pumping costs, pump-lift and aquifer withdrawals embedded within the structure of the dynamic economic optimization model to the cell level information contained in each MODFLOW cell is the mechanism that allows us to more accurately track the impact of optimal agriculturally driven water use decisions on aquifer storage values and pumplift over the 60 year planning horizon. By interactively linking the dynamic economic model to the hydrologic model at the one square mile level of resolution, the integrated modeling approach controls for both the spatial variability in hydrologic response to agricultural groundwater stresses and the location of agricultural stresses. Specifically, the integrated model will more accurately simulate the relationship between hydrologic stresses (groundwater withdrawals) imposed by economic activity and the resulting change in aquifer status than an approach that treats regional land use practices and aquifer characteristics as homogeneous throughout the region . This additional spatial sub-regional detail is essential because it provides policy makers with a tool for targeting specific water uses and/or geographic regions that can most-cost effectively achieve a policy dictated reduction in groundwater use.

EMPIRICAL RESULTS

As reported in Table 4, under existing baseline conditions the NPV for per acre returns over the 60 year planning horizon range from a low of $7,581 in the Castro-Lamb study area (C-L in the Table 4) to a high of $9,101 in the Gaines-Terry study area (G-T in Table 4) when the aquifer characteristics of each specific study area are assumed to be homogenous and are set to their average respective study area values in each study area. For each study area, the scenario labeled **Econ. Base** in bold font identifies the estimated baseline situation when aquifer characteristics are treated as being homogenous across a study area. The scenario labeled **Int. Base** in bold font identifies the baseline condition in each study area when the baseline is estimated using the integrated economic-hydrologic modeling approach to control for heterogeneity in aquifer characteristics at the one square mile level of resolution. For all three study regions, per acre NPV over the 60 year planning horizon is smaller for the integrated modeling approach than for the modeling approach that treats aquifer characteristics as homogenous within a study area. Moreover, the percentage decrease is greatest for the Gaines-Terry study area (-29.8%) which has the largest coefficient of variation for initial pump lift and saturated thickness, and smallest for Castro-Lamb (-3.7%) which had the smallest coefficient of variation for the same aquifer characteristics.

Net Present Value

The remainder of Table 4 compares the percentage change in per acre net income over time for the five conservation policies relative to the baseline condition estimated by the integrated model. The estimated policy outcome for all conservation policies was estimated using the integrated model. Over the 60-year planning horizon, annually reducing the maximum withdrawal level by an additional one percent per year from the initial year baseline level (labeled *1% Red* policy) does not reduce NPV in Castro-Lamb because the restriction is not binding. Under exiting economic incentives groundwater use in this region is forecast to decrease by more than one percent annually. However, the per acre NPV return for the other two areas is negatively affected by the 1% annual reduction policy.

When the annual water use restriction policy is coupled with the bio-tech policy, the NPV for each respective area increases relative to each of their integrated baseline conditions. The increases range from a low of 15.2% in Gaines-Terry to a high of 21.6% in Castro-Lamb. These findings suggest that bio-technology yield increases could potentially be an important aid in defraying groundwater conservation cost.

The three land use retirement policies only minimally affect baseline NPV in each region. The largest NPV reduction is for the Permanent Land Retirement (A) policy in Castro-Lamb which results in a 3% decrease. The Temporary Land Retirement policies consistently impose a lower per acre cost on agriculture than either of the permanent land retirement policies.

Pumping Cell Effects

Table 5 presents the impact that each policy has on the number of agriculturally active (agriculturally pumping) MODFLOW well cells through time. In the initial time period, 371 of the 400 one-square mile MODFLOW cells in Castro-Lamb provide agricultural water supplies. In the Gaines-Terry area only 270 of the MODFLOW cells are agriculturally stressed in the initial year and only 212 Hale-Floyd area cells are stressed in the initial time period. In each study area, under the baseline scenario, a significant fraction of the agriculturally stress cells go dry. Only 69.8% of the initially agriculturally active cells contain water supplies in year 60 in Castro-Lamb. For the other two areas, the abandonment of agricultural wells is even greater as only 41.5% and 36.3% of the Gaines-Terry and Hale-Floyd cells, respectively, remain active in year 60.

The rapid drawdown in the Gaines-Terry area explains the large divergence between the reported per acre net present values for the homogeneous baseline outcome versus the heterogeneous baseline outcome reported in Table 4. Under the current high price of corn, it is more profitable for producers to convert their low-value less-water intensive crops to water intensive corn production. Under homogeneous, or average, aquifer conditions the landowner can keep the majority of his/her irrigated water-intensive corn acreage in production for a considerably longer period of time than possible when the spatial distribution of aquifer characteristics is controlled for. With the integrated modeling approach only 44.4% of the initially active groundwater cells have stored water supplies after twenty years.

Irrigated Acres

As reported in Table 6 irrigated acreage as a share of all crop acreage is significantly less in each study region when the integrated modeling framework is utilized. By the end of the 60-year planning horizon, the baseline irrigated acreage estimate is as much as 83.5% less (Hale-Floyd) when heterogeneity in aquifer characteristics is controlled for. The divergence between the two baseline estimates for the share of irrigated acreage remaining in production overtime is smallest for the Castro-Lamb study area, which has the most homogenous aquifer characteristics. In terms of policy scenarios, both variants of the 1% annual water reduction policy increase the proportion of irrigated acreage in production in year 60, relative to the integrated baseline value, in both Gaines-Terry and Hale-Floyd study areas, even though their respective per acre 60-year net present values are lower than in the baseline. In these two areas, the groundwater use restrictions decreases the rate that the aquifer is mined and thus fewer aquifer cells go dry over time as reported in Table 5. Because the 1% annual water use restriction is not binding in the Castro-Lamb no change in irrigated acreage is observed over time relative to the integrated model baseline. However, when the water restriction is coupled with potential bio-technology yield improvements, the share of acreage irrigated is larger after year 20 for this scenario than for the integrated baseline. The additional yield revenue allows the producer to profitably pump from increasingly greater lifts over time.

Percent of net farm income from irrigated crops

Consistent with the analysis presented in both baseline scenarios the share of net crop income derived from irrigated production decreases over time in each study area. As expected and reported in Table 7, the percentage decline is greater for the integrated baseline than the homogenous baseline. Moreover, the divergence in the two baselines is considerably greater for the Gaines-Terry and Hale-Floyd study areas than the Castro-Lamb study area.

CONCLUSIONS

Baseline projections of expected ground-water use projection can vary significantly between a modeling approach that accounts for heterogeneity in land-use practices and/or aquifer characteristics and an approach that does not even if the study area is relatively homogenous in those characteristics. For the three relatively homogenous study areas considered, per acre NPV was as much as 29.8% larger when groundwater use was modeled under the assumption that aquifer characteristics were homogenous than when accounting for the heterogeneity in these modeling parameters. The future agricultural use of and return to our scare water resources must be accurately determined before any meaningful water policy analysis can begin. The benefits and cost of any conservation program are generally estimated relative to the status quo policy or baseline situation. An inaccurate baseline estimate will lead to poor estimates of potential conservation and policy cost. A viable water policy planning model must be capable of addressing important region-wide economic, environmental, and hydrologic concerns, yet have sufficient spatial and temporal disaggregation to allow for a comprehensive sub-regional analysis of the economic and physical impacts of each proposed policy. Spatial detail is essential because it provides policy makers with a tool for targeting specific water uses and/or geographic regions that can most cost effectively achieve a policy dictated reduction in groundwater use.

References

Barbato, L. S., A. R. Warren, K. Mulligan, E. Fish, J. Johnson, K. A. Rainwater, and D. B. Willis. November 2008. *Impact of Alternative Water Policies on Rural Economies and Aquifer Hydrology: Development of a GIS Data Base of Hydrologic Characteristics*. Center for Geospatial Technology, Texas Tech University. Lubbock, TX: Texas Tech University.

Das, B. 2004. *Towards a Comprehensive Regional Water Policy Model for the Texas High Plains*. Unpublished PhD Dissertation. Lubbock, TX: Texas Tech University.

Das, B., and D.B. Willis. 2004. Towards a Comprehensive Water Policy Model for the Texas High Plains. *Journal of Agricultural and Applied Economics* 36 (2): 510.

Fish, E. 2009. Professor of Natural Resource Management, Department of Natural Resource Management. Texas Tech University. Lubbock, Texas.

Gerik, T., W. Harmon, J. Williams, L. Francis, J. Greiner, M. Magre, A. Meinardus, and E. Steglich. 2003. User's Guide: CroPMan (Crop Production and Management Model). Temple, TX: Blackland Research and Extension Center.

Guru, M.V. and J.E. Horne. "The Ogallala Aquifer." Kerr Center for Sustainable Agriculture. 2000. www.kerrcenter.com/publications/ogallala_aquifer.pdf.

Harmon, W. L. *An Economic Evaluation of Irrigation Water Use over Time on Texas High Plains Farms with a Rapidly Diminishing Water Supply*. 1966. Unpublished thesis. Texas A&M University, College Station, TX.

High Plains Underground Water Conservation Distinct No. 1, No date. The Ogallala Aquifer. Information Paper. Undated. http://www.hpwd.com/ogallala/ogallala.asp (accessed November 20, 2004).

McDonald, M.G., and A.W. Harbaugh. 1988. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model.* USGS Water Resources Investigations Report 83-875.

Ogallala Commons, Press Release, October 10th Conference on Water in Ogallala, NE. No date. http://ogallalacommons.org/docs/ogallala_pr1.doc. (accessed July 13, 2004.)

Stovall, J.N. 2009. "Groundwater Modeling for the Southern High Plains." Unpublished paper. Texas Tech Water Resources Center, Texas Tech University. Lubbock, TX.

Terrell, B. (1998). *Economic Impacts of the Depletion of the Ogallala Aquifer: An Application to the Texas High Plains.* Unpublished Master's thesis. Texas Tech University, Lubbock, TX.

Texas Agricultural Extension Service. *2008. Texas Crop and Livestock Budgets: District 2*. http://jeanann.tamu.tamu.edu/budgets/district/1and2/2008.index.php. (accessed May 15. 2008).

Table 1. Percentage Comparison of Initial year Crop Mix in Each Study Area

		Study Area		
Technology	Crop	Castro-Lamb	Gaines-Terry	Hale-Floyd
Irrigated	Cotton	22.50%	42.57%	38.21%
	Corn	26.69%	0.05%	5.41%
	Peanuts	0.36%	14.50%	0.00%
	Sorghum	6.21%	2.13%	6.44%
	Wheat	26.63%	13.13%	5.72%
	Sub-total	82.39%	72.36%	55.77%
Dryland				
	Cotton	2.08%	20.91%	16.28%
	Corn	0.00%	0.00%	0.00%
	Peanuts	0.00%	0.00%	0.00%
	Sorghum	2.25%	4.09%	6.94%
	Wheat	13.29%	2.63%	21.00%
	Sub-total	17.61%	27.64%	44.23%
Total		100.00%	100.00%	100.00%

Table 2. Percentage Comparison of Study Area Irrigation Technologies

Study Area	Irrigated LEPA	Irrigated Furrow	Irrigated Total	Dryland	Total Crop Acres
Castro-Lamb	61.80%	6.50%	68.30%	14.60%	82.90%
Gaines-Terry	49.20%	1.60%	50.80%	19.40%	70.20%
Hale-Floyd	26.40%	7.90%	34.30%	27.20%	61.50%

Table 3. Summary Statistics for Pump-Lift and Saturated Thickness measured in feet for all Agriculturally Stressed Square Mile Aquifer Cells in the Initial Time Period

Study Area	Statistic	Pump Lift	Saturated Thickness
Castro-Lamb	minimum	195.60	42.55
	maximum	292.46	175.24
	average	252.72	105.03
	Std Dev	16.66	25.35
	CV	0.07	0.24
	Count	371.00	371.00
Hale-Floyd	minimum	193.17	10.35
	maximum	243.36	190.47
	average	219.48	121.91
	Std Dev	11.59	40.06
	CV	0.05	0.33
	Count	213.00	213.00
Gaines-Terry	minimum	36.60	23.97
	maximum	144.76	163.05
	average	97.34	78.39
	CV	0.67	0.48
	Std Dev	20.63	30.96
	Count	270.00	270.00

Note: Each 400 square mile study area contains 400 one-square mile aquifer cells. Not all land above the aquifer model is stressed by agricultural activity in the initial time period as the land may be developed or not suitable for irrigation. The count statistic reports the number of cells agriculturally stressed in each study area in the initial time period.

Table 4: Selected Yearly Per Acre Average Net Income and 60-Year Per Acre Net Present Value

Area	Scenario	Year 10	Year 20	Year 30	Year 40	Year 50	Year 60	NPV
C-L	**Econ. Base**	**$ 323**	**$ 258**	**$ 226**	**$ 218**	**$ 215**	**$ 214**	**$ 7,581**
	Int. Base	**$ 313**	**$ 240**	**$ 217**	**$ 211**	**$ 210**	**$ 209**	**$ 7,301**
	Change Rel. Econ	-2.9%	-6.8%	-4.2%	-3.1%	-2.6%	-2.4%	-3.7%
	1% Red	$ 313	$ 240	$ 217	$ 211	$ 210	$ 209	$ 7,301
	Change Rel. Int.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	1% Red + BioT	$ 345	$ 301	$ 286	$ 302	$ 324	$ 348	$ 8,878
	Change Rel. Int.	10.3%	25.4%	32.2%	42.6%	54.3%	66.8%	21.6%
	Temp Land	$ 305	$ 248	$ 218	$ 212	$ 210	$ 209	$ 7,282
	Change Rel. Int.	-2.5%	3.4%	0.7%	0.2%	0.1%	0.0%	-0.3%
	Perm Land A	$ 289	$ 232	$ 218	$ 212	$ 210	$ 209	$ 7,080
	Change Rel. Int.	-7.7%	-3.3%	0.7%	0.2%	0.1%	0.0%	-3.0%
	Perm Land B	$ 305	$ 248	$ 218	$ 212	$ 210	$ 209	$ 7,282
	Change Rel. Int.	-2.5%	3.5%	0.7%	0.2%	0.1%	0.0%	-0.3%
G-T	**Econ. Base**	**$ 459**	**$ 350**	**$ 208**	**$ 177**	**$ 167**	**$ 163**	**$ 9,101**
	Int. Base	**$ 303**	**$ 175**	**$ 134**	**$ 127**	**$ 124**	**$ 123**	**$ 6,394**
	Change Rel. Econ	-34.0%	-50.0%	-35.5%	-28.6%	-25.7%	-24.4%	-29.8%
	1% Red	$ 288	$ 211	$ 176	$ 159	$ 149	$ 141	$ 6,368
	Change Rel. Int.	-5.2%	20.3%	31.0%	25.8%	20.2%	14.5%	-0.4%
	1% Red + BioT	$ 310	$ 246	$ 221	$ 216	$ 217	$ 220	$ 7,368
	Change Rel. Int.	2.3%	40.5%	65.1%	70.6%	75.2%	78.9%	15.2%
	Temp Land	$ 309	$ 194	$ 136	$ 127	$ 124	$ 123	$ 6,372
	Change Rel. Int.	1.9%	10.6%	1.6%	0.6%	0.3%	0.2%	-0.3%
	Perm Land A	$ 301	$ 188	$ 136	$ 140	$ 123	$ 123	$ 6,279
	Change Rel. Int.	-0.7%	7.3%	1.7%	10.6%	-1.1%	-0.4%	-1.8%
	Perm Land B	$ 309	$ 196	$ 136	$ 127	$ 124	$ 123	$ 6,372
	Change Rel. Int.	1.9%	11.8%	1.7%	0.6%	0.3%	0.2%	-0.3%
H-F	**Econ. Base**	**$ 307**	**$ 302**	**$ 295**	**$ 288**	**$ 264**	**$ 231**	**$ 8,291**
	Int. Base	**$ 281**	**$ 242**	**$ 224**	**$ 213**	**$ 202**	**$ 196**	**$ 7,008**
	Change Rel. Econ	-8.3%	-19.9%	-24.1%	-26.1%	-23.6%	-15.5%	-15.5%
	1% Red	$ 279	$ 237	$ 221	$ 211	$ 206	$ 201	$ 6,964
	Change Rel. Int.	-1.0%	-2.0%	-1.5%	-0.9%	1.9%	2.7%	-0.6%
	1% Red + BioT	$ 305	$ 281	$ 280	$ 286	$ 296	$ 307	$ 8,238
	Change Rel. Int.	8.5%	16.2%	25.3%	34.2%	47.0%	56.7%	17.5%
	Temp Land	$ 276	$ 246	$ 226	$ 215	$ 203	$ 196	$ 6,985
	Change Rel. Int.	-1.8%	1.7%	0.8%	1.2%	0.7%	0.2%	-0.3%
	Perm Land A	$ 267	$ 232	$ 224	$ 216	$ 206	$ 198	$ 6,847
	Change Rel. Int.	-5.3%	-4.3%	0.3%	1.4%	2.3%	1.0%	-2.3%
	Perm Land B	$ 277	$ 242	$ 224	$ 216	$ 206	$ 198	$ 6,978
	Change Rel. Int.	-1.6%	0.1%	0.3%	1.4%	2.3%	1.0%	-0.4%

Table 5: Number of Agriculturally Active Well Cells by Study Area and Scenario

Area	Scenario	Year 0	Year 10	Year 20	Year 30	Year 40	Year 50	Year 60
C-L	**Int. Base**	**371**	**359**	**289**	**267**	**261**	**260**	**259**
	1% Red	371	359	289	267	261	260	259
	Change Rel. Int.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	1% Red + BioT	371	362	294	268	261	260	259
	Change Rel. Int.	0.0%	0.8%	1.7%	0.4%	0.0%	0.0%	0.0%
	Temp Land	371	362	294	269	261	260	259
	Change Rel. Int.	0.0%	0.8%	1.7%	0.7%	0.0%	0.0%	0.0%
	Perm Land A	371	362	294	269	261	260	259
	Change Rel. Int.	0.0%	0.8%	1.7%	0.7%	0.0%	0.0%	0.0%
	Perm Land B	371	362	294	269	261	260	259
	Change Rel. Int.	0.0%	0.8%	1.7%	0.7%	0.0%	0.0%	0.0%
G-T	**Int. Base**	**270**	**194**	**120**	**112**	**112**	**112**	**112**
	1% Red	270	252	193	159	147	143	141
	Change Rel. Int.	0.0%	29.9%	60.8%	42.0%	31.3%	27.7%	25.9%
	1% Red + BioT	270	252	193	159	147	143	141
	Change Rel. Int.	0.0%	29.9%	60.8%	42.0%	31.3%	27.7%	25.9%
	Temp Land	270	205	125	113	113	113	113
	Change Rel. Int.	0.0%	5.7%	4.2%	0.9%	0.9%	0.9%	0.9%
	Perm Land A	270	205	125	113	113	113	113
	Change Rel. Int.	0.0%	5.7%	4.2%	0.9%	0.9%	0.9%	0.9%
	Perm Land B	270	205	125	113	113	113	113
	Change Rel. Int.	0.0%	5.7%	4.2%	0.9%	0.9%	0.9%	0.9%
H-F	**Int. Base**	**212**	**192**	**149**	**123**	**100**	**80**	**77**
	1% Red	212	192	151	132	118	112	104
	Change Rel. Int.	0.0%	0.0%	1.3%	7.3%	18.0%	40.0%	35.1%
	1% Red + BioT	212	192	151	132	118	112	104
	Change Rel. Int.	0.0%	0.0%	1.3%	7.3%	18.0%	40.0%	35.1%
	Temp Land	212	196	156	126	106	80	76
	Change Rel. Int.	0.0%	2.1%	4.7%	2.4%	6.0%	0.0%	-1.3%
	Perm Land A	212	196	156	129	112	87	78
	Change Rel. Int.	0.0%	2.1%	4.7%	4.9%	12.0%	8.8%	1.3%
	Perm Land B	212	196	156	129	112	87	78
	Change Rel. Int.	0.0%	2.1%	4.7%	4.9%	12.0%	8.8%	1.3%

Note: An active well cell is a MODFLOW cell is a one-square mile cell that contains stored water and is agriculturally stressed at a point in time.

Table 6: Irrigated Acres as a Percent of All Crop Acres By Study Area and Scenario

Area	Scenario	Year 0	Year 10	Year 20	Year 30	Year 40	Year 50	Year 60
C-L	**Econ. Base**	**82.39%**	**82.39%**	**46.29%**	**21.51%**	**15.05%**	**12.62%**	**11.56%**
	Int. Base	**82.39%**	**82.39%**	**31.95%**	**13.17%**	**8.92%**	**7.41%**	**6.75%**
	Change Rel. Econ.	0.0%	0.0%	-31.0%	-38.8%	-40.7%	-41.3%	-41.6%
	1% Red	82.39%	82.39%	31.95%	13.17%	8.92%	7.41%	6.75%
	Change Rel. Int.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	1% Red + BioT	82.39%	82.39%	38.81%	15.05%	10.10%	8.49%	7.87%
	Change Rel. Int.	0.0%	0.0%	21.5%	14.3%	13.2%	14.5%	16.6%
	Temp Land	82.39%	74.15%	38.42%	14.35%	9.24%	7.54%	6.81%
	Change Rel. Int.	0.0%	-10.0%	20.2%	9.0%	3.5%	1.7%	0.9%
	Perm Land A	82.39%	74.15%	38.55%	14.37%	9.25%	7.55%	6.81%
	Change Rel. Int.	0.0%	-10.0%	20.7%	9.2%	3.6%	1.8%	0.9%
	Perm Land B	82.39%	74.15%	38.55%	14.37%	9.25%	7.55%	6.81%
	Change Rel. Int.	0.0%	-10.0%	20.7%	9.2%	3.6%	1.8%	0.9%
G-T	**Econ. Base**	**72.36%**	**72.36%**	**52.68%**	**21.79%**	**15.12%**	**12.84%**	**11.92%**
	Int. Base	**72.36%**	**42.88%**	**14.08%**	**5.27%**	**3.66%**	**3.11%**	**2.88%**
	Change Rel. Econ.	0.0%	-40.8%	-73.3%	-75.8%	-75.8%	-75.8%	-75.8%
	1% Red	72.36%	39.24%	21.58%	14.13%	10.60%	8.46%	6.69%
	Change Rel. Int.	0.0%	-8.5%	53.2%	167.9%	189.8%	172.4%	132.1%
	1% Red + BioT	72.36%	39.24%	21.58%	14.13%	10.60%	8.46%	6.69%
	Change Rel. Int.	0.0%	-8.5%	53.2%	167.9%	189.8%	172.4%	132.1%
	Temp Land	72.36%	44.11%	18.07%	5.72%	3.81%	3.18%	2.93%
	Change Rel. Int.	0.0%	2.9%	28.3%	8.4%	4.2%	2.4%	1.7%
	Perm Land A	72.36%	44.12%	18.51%	5.77%	6.49%	2.82%	2.77%
	Change Rel. Int.	0.0%	2.9%	31.4%	9.4%	77.5%	-9.4%	-3.9%
	Perm Land B	72.36%	44.12%	18.51%	5.77%	3.83%	3.19%	2.93%
	Change Rel. Int.	0.0%	2.9%	31.4%	9.4%	4.6%	2.6%	1.7%
H-F	**Econ. Base**	**55.77%**	**55.77%**	**55.77%**	**55.77%**	**55.77%**	**49.71%**	**29.26%**
	Int. Base	**55.77%**	**55.38%**	**33.40%**	**23.25%**	**16.47%**	**8.87%**	**4.83%**
	Change Rel. Econ.	0.0%	-0.7%	-40.1%	-58.3%	-70.5%	-82.2%	-83.5%
	1% Red	55.77%	53.71%	30.09%	20.68%	14.82%	11.58%	8.47%
	Change Rel. Int.	0.0%	-3.0%	-9.9%	-11.0%	-10.0%	30.6%	75.5%
	1% Red + BioT	55.77%	54.98%	31.59%	22.29%	16.38%	13.14%	9.87%
	Change Rel. Int.	0.0%	-0.7%	-5.4%	-4.2%	-0.5%	48.2%	104.4%
	Temp Land	55.77%	50.20%	35.50%	24.20%	18.26%	9.81%	5.06%
	Change Rel. Int.	0.0%	-9.4%	6.3%	4.0%	10.8%	10.6%	4.8%
	Perm Land A	55.77%	50.20%	33.11%	23.16%	18.45%	12.09%	6.09%
	Change Rel. Int.	0.0%	-9.4%	-0.9%	-0.4%	12.0%	36.3%	26.2%
	Perm Land B	55.77%	50.20%	33.11%	23.16%	18.45%	12.09%	6.09%
	Change Rel. Int.	0.0%	-9.4%	-0.9%	-0.4%	12.0%	36.3%	26.2%

Table 7: Percent of net crop income from Irrigated acres by Study Area and Scenario

Area	Scenario	Year 0	Year 10	Year 20	Year 30	Year 40	Year 50	Year 60
C-L	**Econ. Base**	**93.11%**	**89.39%**	**58.92%**	**31.59%**	**23.27%**	**20.00%**	**18.55%**
	Int. Base	**93.11%**	**89.07%**	**44.14%**	**21.03%**	**15.14%**	**12.99%**	**12.04%**
	Change Rel. Econ	0.0%	-0.4%	-25.1%	-33.4%	-34.9%	-35.1%	-35.1%
	1% Red	93.11%	89.07%	44.14%	21.03%	15.14%	12.99%	12.04%
	Change Rel. Int.	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	1% Red + BioT	93.11%	89.23%	52.48%	24.46%	17.59%	15.28%	14.40%
	Change Rel. Int.	0.0%	0.2%	18.9%	16.3%	16.2%	17.6%	19.6%
	Temp Land	93.11%	83.47%	51.11%	22.62%	15.58%	13.17%	12.12%
	Change Rel. Int.	0.0%	-6.3%	15.8%	7.5%	2.9%	1.4%	0.6%
	Perm Land A	93.11%	88.16%	54.84%	22.65%	15.59%	13.17%	12.12%
	Change Rel. Int.	0.0%	-1.0%	24.3%	7.7%	3.0%	1.4%	0.7%
	Perm Land B	93.11%	83.47%	51.26%	22.65%	15.59%	13.17%	12.12%
	Change Rel. Int.	0.0%	-6.3%	16.1%	7.7%	3.0%	1.4%	0.7%
G-T	**Econ. Base**	**90.67%**	**93.48%**	**85.24%**	**58.89%**	**47.72%**	**43.00%**	**40.92%**
	Int. Base	**90.67%**	**79.50%**	**46.37%**	**22.83%**	**16.87%**	**14.71%**	**13.84%**
	Change Rel. Econ	0.0%	-15.0%	-45.6%	-61.2%	-64.6%	-65.8%	-66.2%
	1% Red	90.67%	77.00%	59.31%	46.61%	38.66%	32.98%	27.71%
	Change Rel. Int.	0.0%	-3.1%	27.9%	104.2%	129.1%	124.3%	100.2%
	1% Red + BioT	90.67%	77.10%	59.58%	47.00%	39.13%	33.49%	28.21%
	Change Rel. Int.	0.0%	-3.0%	28.5%	105.9%	131.9%	127.7%	103.8%
	Temp Land	90.67%	80.31%	53.77%	24.37%	17.47%	15.01%	14.03%
	Change Rel. Int.	0.0%	1.0%	16.0%	6.7%	3.5%	2.1%	1.4%
	Perm Land A	90.67%	82.43%	56.80%	24.54%	27.08%	13.47%	13.35%
	Change Rel. Int.	0.0%	3.7%	22.5%	7.5%	60.5%	-8.4%	-3.5%
	Perm Land B	90.67%	80.32%	54.50%	24.54%	17.53%	15.04%	14.04%
	Change Rel. Int.	0.0%	1.0%	17.5%	7.5%	3.9%	2.2%	1.5%
H-F	**Econ. Base**	**83.84%**	**73.27%**	**72.45%**	**71.80%**	**71.12%**	**64.16%**	**42.50%**
	Int. Base	**83.84%**	**65.53%**	**48.20%**	**35.51%**	**26.19%**	**15.01%**	**8.50%**
	Change Rel. Econ	0.0%	-10.6%	-33.5%	-50.5%	-63.2%	-76.6%	-80.0%
	1% Red	83.84%	67.03%	44.52%	32.37%	24.01%	19.11%	14.34%
	Change Rel. Int.	0.0%	2.3%	-7.6%	-8.8%	-8.3%	27.3%	68.8%
	1% Red + BioT	83.84%	69.83%	48.03%	36.87%	28.89%	24.20%	19.07%
	Change Rel. Int.	0.0%	6.6%	-0.4%	3.8%	10.3%	61.3%	124.4%
	Temp Land	83.84%	59.49%	50.67%	36.83%	28.59%	16.48%	8.87%
	Change Rel. Int.	0.0%	-9.2%	5.1%	3.7%	9.2%	9.8%	4.4%
	Perm Land A	83.84%	61.29%	50.19%	35.60%	28.95%	19.89%	10.57%
	Change Rel. Int.	0.0%	-6.5%	4.1%	0.2%	10.6%	32.5%	24.5%
	Perm Land B	83.84%	59.72%	48.02%	35.60%	28.95%	19.89%	10.57%
	Change Rel. Int.	0.0%	-8.9%	-0.4%	0.2%	10.6%	32.5%	24.5%

Figure 1: The Ogallala Aquifer System

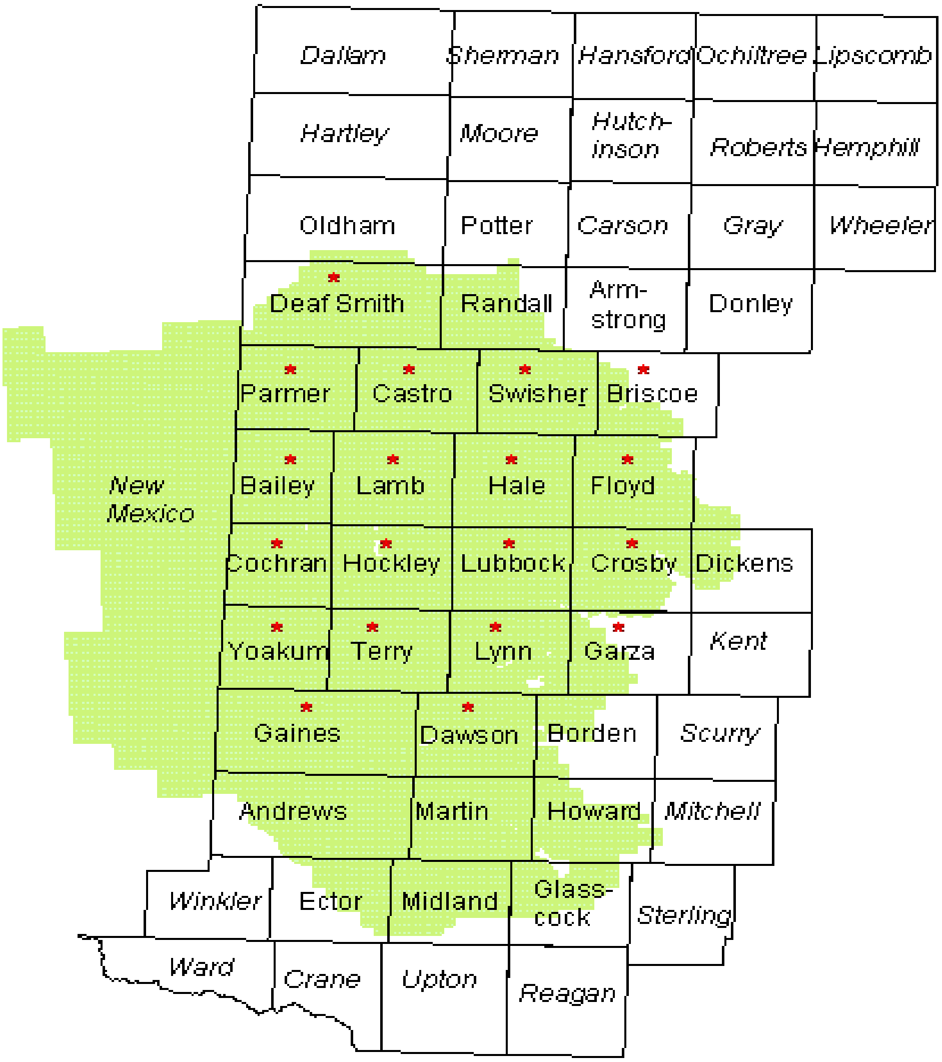

Figure 2: The Southern Ogallala Aquifer
Solid colored area identifies Southern Ogallala Aquifer
Stars identify the 19 heavy agricultural water using counties in the Texas High Plains above the aquifer that account for 97 percent of all agricultural groundwater use.

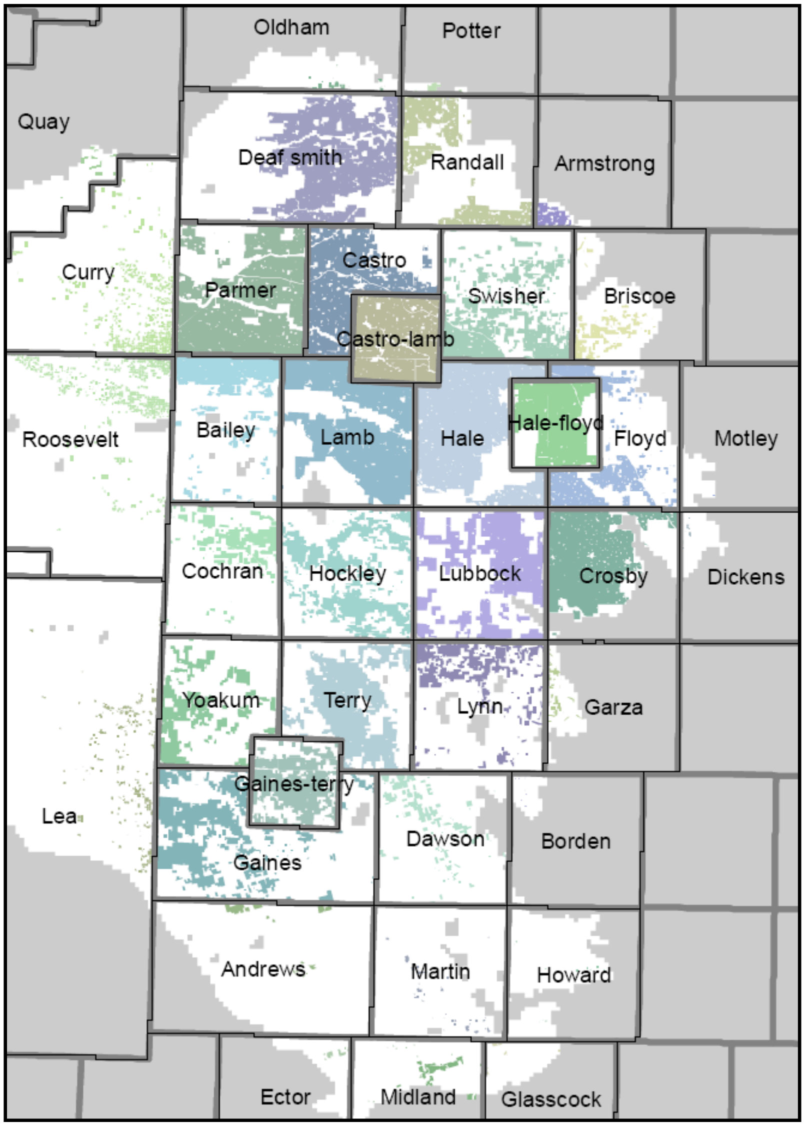

Figure 3: Location of the three THP study areas (Castro-Lamb, Hale-Floyd, and Gaines-Terry).