The Impact of Spatial Variation in Land Use Patterns and Aquifer Characteristics on the Agricultural Cost of Groundwater Conservation for the Southern Ogallala Aquifer

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Abstract

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Introduction

The construction of economic water policy models for irrigated agriculture typically requires simplifying assumptions about the location of groundwater supplies, hydrologic parameters, and land use practices. Even though the hydrologic and economic models are often individually complex, differences in modeling scale often requires aggregating the hydrologic parameters and economic variables to a level that loses important spatial variability. For example, the hydrologic modeling of aquifer depletion by irrigation withdrawals commonly use projected pumping values provided by economic production models that often do not capture the heterogeneous nature of the depth to groundwater and the energy needed to lift the groundwater over time. In a prior study, Das and Willis (2004) linked a spatially disaggregated hydrologic model of the Southern Ogallala Aquifer to a dynamic economic model of agricultural production 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 cumulative water savings when conservation policy cost and water saving were measured relative to the inaccurate baseline condition.

Credible groundwater policy models are needed to sustainably manage the Southern Ogallala Aquifer because annual withdrawals are at least 10 times greater than the natural recharge rate (Guru and Horne 2000). 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). This current research extends prior policy modeling efforts by controlling for the effects of spatial heterogeneity in land cover, irrigation technology, and aquifer characteristics through the use of a detailed GIS data set to estimate expected future baseline ground water use for three areas of the Texas High Plains that intensively use available groundwater supplies for irrigation.

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 seek to show 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.

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. Each of the three selected 400 square mile study sites were chosen on the basis of the consistency of the agricultural land-use practices and hydrologic characteristics within the study area. Despite our efforts to identify three areas of the THP that are relatively homogeneous within their boundaries regarding land use practices and aquifer characteristics considerable spatial variation still exists within each study site.

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 2004-2008).

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 data for the years 2004-2008 using data reported by the Texas Agricultural Statistics Service. Crop LDP were calculated as specified in the Farm and Rural Investment Act of 2002 under the assumption that the 2004-2008 average crop market price was realized. Under the average assumed crop price no LDP were paid on Sorghum, Peanuts, or Corn. 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) $$Max\ PVNI = \sum_{t}^{60} NI_t * (1+r)^{-t}$$

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

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

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

(7) $$PER\ ACRE\ WATER\ USE_t = \sum_c \sum_i \Theta_{cit} * WP_{cit}$$

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

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

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

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

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

(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* ($IRENERGYCOST_{cit}$), 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

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[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.

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 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 does a better job of controlling for both for 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.

In the empirical results section we focus on reporting the differences in establishing a 60 year baseline condition that treats land-use practices as constant within a region versus an alternative baseline that explicitly acknowledges and controls for within region heterogeneity of land use practices and aquifer characteristics. Our presentation is limited to showing the significant differences between expected baseline economic and irrigated water use data generated by the two alternative modeling approaches under existing water policy regulations, economic incentives, and irrigation technology. Thus our analysis is limited to reporting the status quo, or baseline, optimal producer response to increasing water scarcity over time estimated by the two modeling approaches for each study region.

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 ground water 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.

EMPIRICAL RESULTS

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 within each respective study region. Even though average land use practices and aquifer characteristics are significantly different between each selected study area region, the individual regions were selected for analysis because the collected GIS data indicated that the land use practices and aquifer characteristics within each region were relatively homogenous relative to degree of variability observed in most area of the THP.

As reported in Table 1, the NPV of per acre returns over the 60 year planning horizon ranged from a low of $3,425 to a high of $5,314 among the three study regions when each region was modeled as having homogenous (average) land use practices and aquifer characteristics. The Gaines-Terry study area had the largest per acre return. The high return is attributable to the high valued irrigated corn and peanut acreage in this region. Peanuts are not grown in the less well drained soils of the two other study areas. Per acre net returns are also higher in the Gaines-Terry study region because well pump-lift is less than half as deep than for the other two areas. Initial year 1 pump-lift is 99 feet in Gaines-Terry, versus 222 feet in Hale-Floyd and 256 feet in Castro-Lamb. Even though the Hale-Floyd study region has the fewest irrigated acres in year 1 at 87,808, the region withdraws more groundwater then both Castro-Floyd which has 174,848 irrigated acres in year1 and Gaines-Terry with 130,048 acres in year 1. The cumulative 60 year groundwater withdrawal level of 7.45 MAF in Hale-Floyd exceeds the 4.90 MAF withdrawal level for Castro-Lamb and the 5.21 MAF withdrawn in the Gaines-Terry study area. The greater withdrawal level for Hale-Floyd is primarily attributable to fewer alternative cropping alternatives in this region in the face of increasing groundwater pump lifts.

When the heterogeneity of aquifer characteristics and land use practices in each region are explicitly modeled the simulated empirical results are quite different. Per acre NPV is as much as 82% less in one region (Gaines-Terry) and cumulative groundwater use is as much as 118% less (Gaines-Terry). In controlling for the aquifer's spatial variability, the integrated modeling approach was able to account for the increasing percentage of year 1irrigated acreage that is converted to dryland production overtime due to groundwater exhaustion in specific sub-areas of the study area. As show in table 7, at the end of the 60 year simulation, only 68.2% of the aquifer model cells in the Castro-Lamb study region that provided groundwater supplies to this study region in year 1 still had water supplies. In the other two regions the complete mining of the groundwater is even more dramatic. Only 41.9% of the aquifer cells that supplied groundwater to the Gaines-Terry area in year 1 still had saturated thickness at the end of the simulation. The Hale-Floyd region fared slightly better, 51.2% of the aquifer cells that provided groundwater to this region still had stored water supplies at the end of the simulation. This single fundamental difference in the two modeling approaches accounts for the significant differences in estimated per acre net return and cumulative groundwater use over time.

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 82.5% larger when groundwater use was modeled under the assumption that land use and aquifer characteristics were homogenous than when accounting for the heterogeneity in these modeling parameters. Moreover, cumulative groundwater use is as much as 118% greater when the modeling approach fails to accurately reflect the heterogeneity in land use practices and aquifer characteristics.

Failure to account for spatial heterogeneity, overstated expected agricultural net returns and water use over a 60 year planning horizon. 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.

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. Per Acre Net Present Value for Sixty Year Planning Horizon by Study Area and Sub-Study Area for Alternative Estimation Techniques ($s/acre)

Study Area	Sub-Area	LU[a] AQ[b]	Average Average	Hetero[1] Average	Average Hetero	Hetero[1] Hetero
Castro-Lamb			$3,425	$3,534	$3,267	$3,372
	Castro-Lamb-Castro		$3,298			$3,152
	Castro-Lamb-Hale		$3,297			$2,788
	Castro-Lamb-Lamb		$4,564			$4,453
Gaines-Terry			$5,314	$4,538	$3,372	$2,911
	Gaines-Terry-Gaines		$3,887			$2,742
	Gaines-Terry-Terry		$5,240			$3,170
	Gaines-Terry-Yoakum		$7,040			$3,348
Hale-Floyd			$4,636	$4,634	$3,802	$3,694
	Hale-Floyd-Floyd		$4,997			$4,708
	Hale-Floyd-Hale		$4,360			$2,927

[1] For Study Area value calculated as weighted average of appropriate Sub-Area values weighted by subarea acreage to total acreage

[a] LU is land use practices

[b] AQ is aquifer characteristics

Table 2. Total Cumulative Groundwater Withdrawals over 60 Year Planning Horizon by Study Area and Sub-Study Area for Alternative Estimation Techniques (acre-feet)

Study Area	Sub-Area	LU[a] AQ[b]	Average Average	Hetero[1] Average	Average Hetero	Hetero[1] Hetero
Castro-Lamb			6,169,984	6,179,367	5,075,214	5,232,687
	Castro-Lamb-Castro		4,903,830			4,194,434
	Castro-Lamb-Hale		310,643			185,097
	Castro-Lamb-Lamb		964,894			853,155
Gaines-Terry			5,211,377	5,026,031	2,468,473	2,385,278
	Gaines-Terry-Gaines		3,448,629			1,890,333
	Gaines-Terry-Terry		1,092,532			402,760
	Gaines-Terry-Yoakum		484,870			92,186
Hale-Floyd			7,453,380	6,740,355	3,637,897	3,490,819
	Hale-Floyd-Floyd		3,004,264			2,300,050
	Hale-Floyd-Hale		3,736,090			1,190,770

[1] For Study Area value calculated as weighted average of appropriate Sub-Area values weighted by subarea acreage to total acreage
[a] LU is land use practices
[b] AQ is aquifer characteristics

Table 3. Total Cumulative Per acre Ground Water Withdrawals per Year 1 irrigated acre over the 60 Year Planning Horizon by Study Area and Sub-Study Area for Alternative Estimation Techniques (acre-feet/acre)

Study Area	Sub-Area	LU[a] AQ[b]	Average Average	Hetero[1] Average	Average Hetero	Hetero[1] Hetero
Castro-Lamb			35.3	35.3	29.0	29.9
	Castro-Lamb-Castro		37.6			32.2
	Castro-Lamb-Hale		29.3			17.5
	Castro-Lamb-Lamb		28.5			25.2
Gaines-Terry			40.1	38.6	19.0	18.3
	Gaines-Terry-Gaines		37.9			20.8
	Gaines-Terry-Terry		40.5			14.9
	Gaines-Terry-Yoakum		40.4			7.7
Hale-Floyd			84.9	76.8	41.4	39.8
	Hale-Floyd-Floyd		90.6			69.3
	Hale-Floyd-Hale		68.4			21.8

[1] For Study Area value calculated as weighted average of appropriate Sub-Area values weighted by subarea acreage to total acreage

[a] LU is land use practices

[b] AQ is aquifer characteristics

Table 4. Percent of Cumulative Groundwater Withdrawals for Alternative Estimation Techniques by Study Area and Sub-Study Areas Relative to Cumulative Groundwater Withdrawals under Average Land Use and Aquifer Characteristic Conditions

Study Area	Sub-Area	LU[a] AQ[b]	Average Average	Hetero Average	Average Hetero	Hetero Hetero
Castro-Lamb			100.0%	100.2%	82.3%	84.8%
	Castro-Lamb-Castro		100.0%			85.5%
	Castro-Lamb-Hale		100.0%			59.6%
	Castro-Lamb-Lamb		100.0%			88.4%
Gaines-Terry			100.0%	96.4%	47.4%	45.8%
	Gaines-Terry-Gaines		100.0%			54.8%
	Gaines-Terry-Terry		100.0%			36.9%
	Gaines-Terry-Yoakum		100.0%			19.0%
Hale-Floyd			100.0%	90.4%	48.8%	46.8%
	Hale-Floyd-Floyd		100.0%			76.6%
	Hale-Floyd-Hale		100.0%			31.9%

[a] LU is land use practices
[b] AQ is aquifer characteristics

Table 5. Percentage of Cropland Irrigated in Year 1 and Year 60 by Study Area and Estimation Technique

Study Area	Year 1 Percent Irrigated	LU[a] AQ[b]	Year 60 Percent Acreage Irrigated: Average Average	Hetero[1] Average	Average Hetero	Hetero[2] Hetero
Castro-Lamb	82.4%		12.1%	13.0%	7.0%	8.0%
Castro-Lamb-Castro	81.8%		13.4%			7.3%
Castro-Lamb-Hale	79.6%		13.1%			4.5%
Castro-Lamb-Lamb	85.5%		11.5%			11.5%
Gaines-Terry	72.4%		11.9%	20.3%	2.8%	4.7%
Gaines-Terry-Gaines	78.7%		19.9%			5.7%
Gaines-Terry-Terry	57.3%		22.8%			3.1%
Gaines-Terry-Yoakum	71.0%		20.9%			1.0%
Hale-Floyd	55.8%		41.8%	33.5%	7.3%	12.7%
Hale-Floyd-Floyd	48.9%		48.9%			30.9%
Hale-Floyd-Hale	60.9%		24.7%			1.9%

[1] Study area value calculated as a weighted average from sub-area Average/Average results using sub-acreage share of total study area acreage as the weight

[2] Study area value calculated as a weighted average from sub-area Hetero/Hetero results using sub-acreage share of total study area acreage as the weight

[a] LU is land use practices

[b] AQ is aquifer characteristics

Table 6. Year 1 and Year 60 Average Pump Lifts for Irrigation Wells by Study Area and Estimation Technique (feet to water table)

Study Area	Year 1 Pump Lift	LU[a] AQ[b]	Year 60 Pump Lift Average Average	Hetero[1] Average	Average Hetero	Hetero[2,3] Hetero
Castro-Lamb	256.3		303.3	302.2	310.0	309.7
Castro-Lamb-Castro	259.3		306.0			316.7
Castro-Lamb-Hale	252.5		292.4			284.2
Castro-Lamb-Lamb	247.1		290.4			290.1
Gaines-Terry	99.5		135.1	134.9	129.7	126.2
Gaines-Terry-Gaines	97.5		136.9			126.9
Gaines-Terry-Terry	103.3		126.0			120.8
Gaines-Terry-Yoakum	115.1		139.3			138.3
Hale-Floyd	222.0		240.9	238.1	268.4	260.2
Hale-Floyd-Floyd	226.7		240.9			257.9
Hale-Floyd-Hale	214.2		236.3			265.7

[1] Average study area pump lift is a weighted acreage average of the sub-area pump lifts calculated using average subarea land use practices and average subarea aquifer characteristics.

[2] Average pump lift for those cells that had agricultural withdrawals in year 1 and still had saturated thickness in year 60. Cells that went dry during the simulation are excluded from the average pump lift calculation.

[3] Average study area pump lift is cell weighted average of all cells still pumping agricultural groundwater in year 60 in each sub-area of the study area.

[a] LU is land use practices

[b] AQ is aquifer characteristics

Table 7. Percentage of Year 1 Active Irrigated Well Cells with Saturated Thickness in Year 60 by Estimation Technique

Study Area	Sub-Area	LU[a] AQ[b]	Average Hetero	Hetero[1] Hetero
Castro-Lamb			69.7%	68.2%
	Castro-Lamb-Castro			64.2%
	Castro-Lamb-Hale			57.1%
	Castro-Lamb-Lamb			84.6%
Gaines-Terry			41.1%	41.9%
	Gaines-Terry-Gaines			45.2%
	Gaines-Terry-Terry			33.9%
	Gaines-Terry-Yoakum			25.0%
Hale-Floyd			37.1%	51.2%
	Hale-Floyd-Floyd			66.9%
	Hale-Floyd-Hale			26.8%

[1] Study Area percentage is calculated at the summation of all sub-study area cells in year 60 having saturated thickness that were agriculturally active in year 1 divided by the total number of agriculturally active cells in the study area in year 1.
[a] LU is land use practices
[b] AQ is aquifer characteristics

Table 8. Year 1 and Year 60 Average Saturated Thickness for all Cells that were Agriculturally Active in Year 1 by Study Area and Estimation Technique

	Year 1		Year 60 Saturated Thickness			
	Saturated	LU[a]	Average	Hetero[1]	Average	Hetero[2]
Study Area	Thickness	AQ[b]	Average	Average	Hetero	Hetero
Castro-Lamb	101.2		16.3	16.5	24.5	22.5
Castro-Lamb-Castro	108.8		17.9			20.8
Castro-Lamb-Hale	72.3		10.8			31.0
Castro-Lamb-Lamb	78.9		12.9			25.3
Gaines-Terry	76.2		12.9	12.5	34.1	36.5
Gaines-Terry-Gaines	82.4		12.3			39.7
Gaines-Terry-Terry	51.5		13.3			24.2
Gaines-Terry-Yoakum	59.5		11.5			24.6
Hale-Floyd	117.1		31.8	34.9	17.8	27.8
Hale-Floyd-Floyd	126.5		57.1			31.1
Hale-Floyd-Hale	101.4		21.4			14.9

[1] Study Area saturated thickness for all cells that were providing agricultural groundwater supplies in year 1 and is calculated as the acreage weighted average for the ending average saturated thickness values in each sub-area estimated under the assumption of average land use practices and average aquifer characteristics.
[2] Study Area saturated thickness for all cells that were providing agricultural groundwater supplies in year 1 and is calculated as the acreage weighted average for the ending average saturated thickness values in each sub-area estimated controlling for heterogeneous land use practices and heterogeneous aquifer characteristics.
[a] LU is land use practices
[b] AQ is aquifer characteristics

Figure 1: The Ogallala Aquifer System

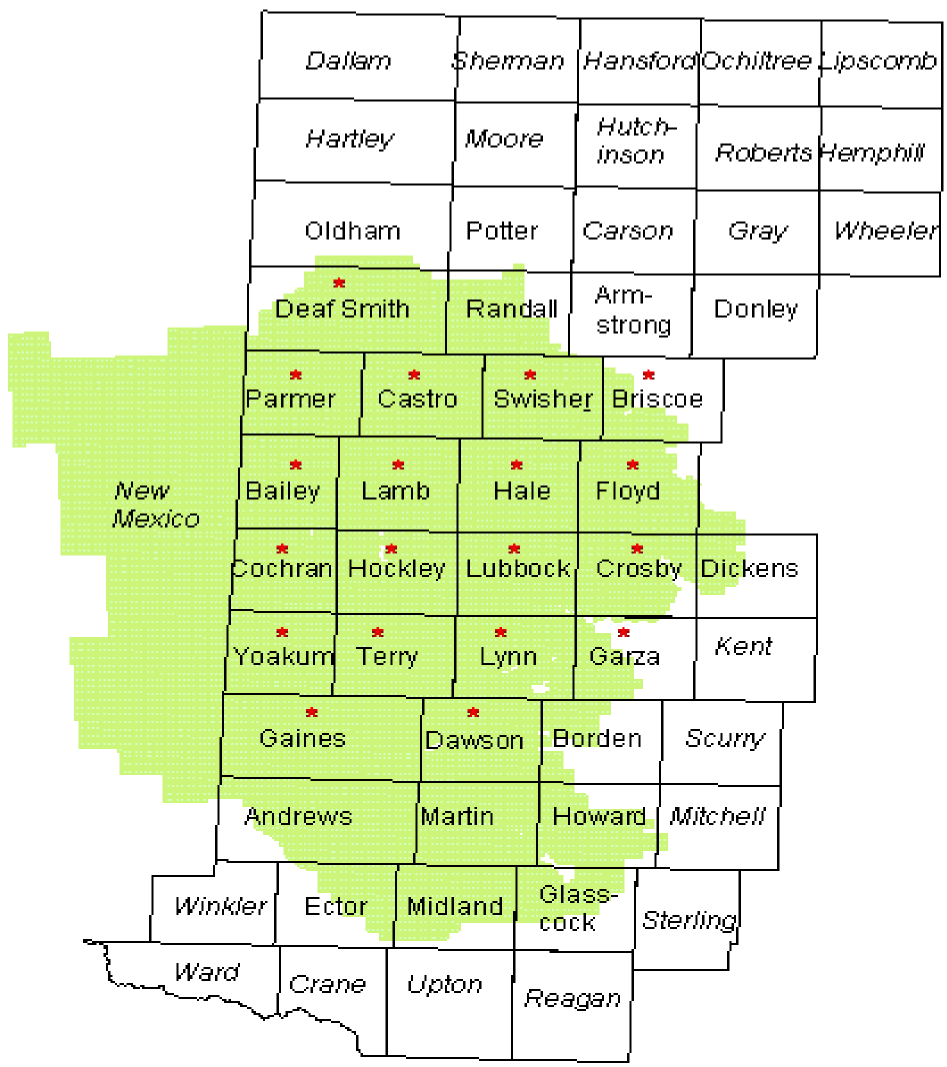

Figure 2: The Southern Ogallala Aquifer

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.

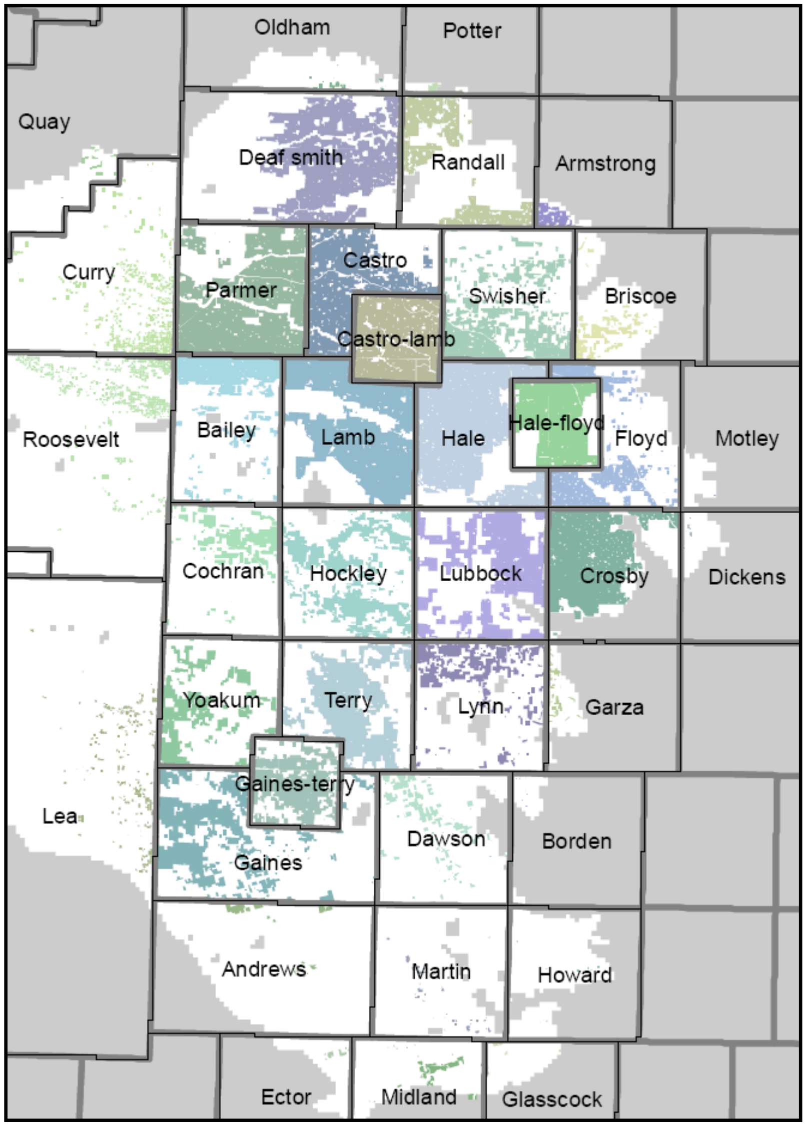

Figure 3: Location of the three THP study areas (Castro-Lamb, Hale-Floyd, and Gaines-Terry).