Towards a Comprehensive Regional Water Policy Model for the Texas High Plains

Biswaranjan Das[1], David B. Willis[2], and Jeffrey W. Johnson[3]

Selected Paper Presented at the Meetings of the Southern Agricultural Economics Association

Tulsa, Oklahoma, February 14-18, 2004

[1] Graduate Student, Department of Agricultural and Applied Economics, Texas Tech University. Box 42132, Lubbock, TX 79409-2132. Phone: (806) 742 0277, ext 226. Email:BISWARANJAN.DAS@TTU.EDU

[2] Assistant Professor, Department of Agricultural and Applied Economics, Texas Tech University. Box 42132, Lubbock, TX 79409-2132. Phone: (806) 742 0277, ext 238. Email: DAVID.WILLIS@TTU.EDU (CONTACT PERSON)

[3] Graduate Student, Department of Agricultural and Applied Economics, Texas Tech University. Box 42132, Lubbock, TX 79409-2132. Phone: (806) 742 2852. Email: JEFF.JOHNSON@TTU.EDU

Introduction

Irrigated agriculture in the Southern High Plains of Texas (SHP) is heavily dependent upon groundwater sources. The major source of groundwater is the Ogallala aquifer which is one of the largest aquifer systems in the world stretching across parts of eight states and under lays about 174,000 square miles (HPWD, 2003). The reliance on groundwater to satisfy water demand in the SHP is attributable to limited surface supplies and the relatively high cost of developing surface water storage facilities.

Irrigated agriculture is a major contributor to the SHP economy and is responsible for 90 percent of all Southern Ogallala aquifer withdrawals. After World War II, advances in irrigation technology combined with economically abundant Ogallala aquifer supplies, low energy prices, and temperate weather conditions, spurred large scale irrigation development. Irrigated agriculture soon became the major groundwater user as agricultural producers took advantage of irrigation technology advances and Texas groundwater law that granted landowners a complete property right to all groundwater reserves beneath their land. In 2002, approximately 5.0 million SHP crop acres were irrigated, approximately 40% less than the 8.1 million acres irrigated in the late 1960s (TASS, 2004). The reduction in irrigated acreage primarily resulted from increased energy pumping cost due to water table declines and resultant increased pump-lifts. Approximately 50 percent of the Southern Ogallala aquifer initial reserves have been mined since the introduction of irrigation technology to the SHP in the 1940s. Despite the declining aquifer level and irrigated acreage reduction, the annual production value of the four major irrigated field crops (cotton, wheat, corn, and grain sorghum) still has a significant economic impact on the SHP economy. Annual gross receipts are 1.9 billion dollars for these four irrigated crops, and their total annual economic impact on the SHP economy is approximately $6.5 billion (Arabiyat, 1998).

Recent Texas legislation (Senate Bills 1 and 2) explicitly recognized the growing scarcity of Texas's groundwater supplies, and required the Texas Water Development Board (TWDB) to develop a statewide water use plan that incorporates locally developed regional water plans. In accordance with Senate Bill 2, in November of 2002, TWDB divided Texas into 16 groundwater management areas (GMAs) in November 2002. Each GMA is identified by well-defined hydrologic boundaries, and were formed to facilitate joint planning between groundwater conservation districts and municipal jurisdictions sharing the same groundwater resource. Groundwater Management Area 2 is the designation given to the Southern Ogallala aquifer management area of the SHP.

Throughout Texas, various water planning groups regularly meet to evaluate water management strategies designed to meet current and projected future demand (Water for Texas, 2002). The primary strategies include water conservation, demand management, reuse of wastewater, expanded use of existing supplies (including systems optimization and conjunctive use of resources), allocation of reservoir storage to new uses, subordination of water rights through voluntary agreements, enhancement of existing sources, and the establishment of water markets to more efficiently allocate scarce water supplies. To evaluate the effectiveness of these strategies, there is a need for a spatially and temporally disaggregated model that can capture the variation in water use within regions and through time.

Previous SHP economic studies of irrigated groundwater use have accounted for spatial differences in cropping patterns and crop yields but have modeled the Southern Ogallala aquifer as a homogenous resource either throughout the region, or at the county geographic level.

However, substantial variation exists both within the SHP, and the various counties of the SHP, with respect to the aquifer's physical characteristics, water use, and cropping practices.

Pure economic models cannot adequately capture aquifer variability and transient changes and are likely to provide inaccurate estimates of economic costs and/or water savings associated with a given water policy. The spatial variation in hydrologic stresses imposed on the aquifer due to ground water withdrawals cannot be adequately captured in a pure economic model. Furthermore, drawdown and recharge rates vary from one locale to another. As a result, not all counties within SHP overlaying the Ogallala aquifer or all regions within a county are confronted by the same degree of crisis. There is a clear need to account for the spatial variability of hydrologic characteristics when constructing water policy models to more accurately estimate economic policy cost and the level of water conserved.

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 a comprehensive water policy model that links the dynamic economic model to a spatially and temporally disaggregated hydrology model. We show that even a well-designed economic model has severe limitations in water policy analysis when it is not coupled to a valid hydrology model due to the spatial variability (heterogeneity) of the aquifer hydrologic characteristics in the modeled region. Conventional economic water policy models are non-comprehensive (non-integrated) and are generally constructed under the assumption that the hydrologic relations existing within region, or within a county sub-region, are homogenous for all areas within the region or county when considerable variability exits. Our presentation is limited to showing the significant differences in the economic and irrigated water use data generated by the two alternative modeling approaches for existing water policy, economic incentives, and irrigation technology. That is, our analysis is limited to reporting the status quo, or baseline, optimal producer response to increasing water scarcity over time. The cost-effectiveness of a proposed water conservation policy is normally measured against the status quo baseline policy when determining the economic net benefit and/or quantity of water conserved by the proposed water policy. If the baseline condition is inaccurately measured subsequent estimates of policy cost and conservation savings will be inaccurately measured.

Economic Model

The economic model used in this study is a modification of the model developed by Johnson (2003). Johnson's model determined the optimal agricultural water extraction time path to maximize the present value of agricultural net returns over a 50 year planning horizon. The Crop Production and Management Model (CROPMAN) was used to develop the production functions describing the yield response to applied water. CROPMAN requires the user to input data crop, irrigation system, soil type, and weather data. In all, CROPMAN was used to develop county specific irrigated crop production functions for the five dominant irrigated crops in the 19 county study area (95 equations in all). These five crops are corn, cotton, grain sorghum, peanuts, and wheat and collectively account for 97 percent of agricultural crop water use in the study area. In developing the county specific crop response functions, the production techniques and timing of cultural practices were held constant, in each individual county, and only the quantity if irrigation water applied was varied. Irrigation timing was also held constant with the quantity of irrigation water applied divided between the various irrigation dates. The simulated crop yields estimated by CROPMAN were recorded for each water application level and used to estimate the county specific crop yield response functions assuming a quadratic functional form with per acre yield as the dependent variable and applied irrigation water as the independent variable. The quadratic form was used to ensure a global maximum would be achieved in the optimization model. To provide a dryland alternative to irrigation, county specific average dryland yields were determined for each of the crops assuming average weather conditions and representative management techniques.

County specific data for each model include county land area, county land area overlying the Ogallala Aquifer, average annual recharge, specific yield for the aquifer, initial saturated thickness, initial average pump lift, initial average well yield, initial average acres served per well, and the initial number of irrigated and dryland acres by crop. The variable costs for dryland crop production and the additional costs for irrigation were taken from enterprise budgets developed by the Texas Agricultural Extension Service for Texas Extension District 2. 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, energy price of $0.0633 per KWH, and pump engine efficiency of 50%. Other costs include the initial cost of the irrigation system of $280 per acre, annual depreciation percentage of 5%, irrigation labor of 2 hours per acre, labor cost of $8 per hour, annual maintenance cost of 8% of initial cost, and a discount rate of 3%.

To provide the economic model a means to capture the impact of agricultural water use on aquifer reserves, pump-lift, pumping cost, and net agricultural returns over a 50 year planning horizon, two equations of motion were developed to monitor pump-lift and aquifer saturated thickness through time. As previously noted, the development of representative equations applicable to an entire county requires some simplifying assumptions. Four crucial assumptions concern the values assigned to (1) average recharge rate; (2) average saturated thickness; (3) initial average water table elevation; (4) and the assumption that per acre water withdrawals are uniform across the county. By making these four assumptions the researcher is confident that the data generated and provided to the policy analyst is qualitatively correct, however the researcher is generally much less confident with regard to the magnitude of the estimated values.

Equation of Motion

The recursive equations used to estimate the relationship between management choices (crops irrigated and quantity of water applied per acre) made at time t and the value of the state variables (pumping lift and remaining groundwater stock) at time t+1 are captured using two equations of motion. Assuming a hydrological region is homogeneous, the equation of motion for pump lift at time t for a representative acre is given by the following hydrological relation:

(1) $$L_{t+1} = L_t + 1/SY * \{[P_t - RCH_t]/12\}$$

where L_{t+1} is the pump-lift in feet at time t+1 , L_t is the pump lift in time period t. SY is specific yield, the percentage of aquifer volume available for storing water and has a value of 0.15. The variable P_t is average water use per irrigated acre measured in acre inches per acre for all irrigated crops, and RCH_t is net recharge in acre feet to the aquifer from all sources including groundwater return flow. The 12 in the denominator converts acre-inches to acre-feet. The second equation of motion, which is inversely related to the first, also uses a recursive relation to model the change in aquifer saturated thickness over time. The general form of this equation when applied to a homogenous representative acre in a given county is:

(2) $$ST_{t+1} = ST_t - 1/SY * \{[P_t - RCH_t]/12\}$$

where ST_{t+1} is the aquifer saturated thickness in feet at time t+1, ST_t is the aquifer saturated thickness in time period t. As before, SY is specific yield and has a value of 0.15, P_t is average water use per irrigated acre measured in acre inches per acre, RCH_t is net recharge in acre feet to the aquifer from all sources including groundwater return flow and the numerical value 12 in the denominator converts inches to feet.

County wide values for recharge, initial saturated thickness and pumping head (lift) are average values and were calculated from the data sets used to parameterize Stovall's (2001) hydrology model of the SHP. In Stovall's hydrology model, the values for these variables were estimated at the cell level (each cell representing one square mile), and the average county values are the average of all the cells in each county (approximately 900 cells per county).

Per acre pumping cost (PC) for crop c in period t is calculated as:

(3) $$PC_{c,t} = \{(EF*(L_t + 2.31*PSI)*EP)/(EFF)\}*(WA_{c,t})$$

where EF is the Energy Use Factor for Electricity that has a value of 0.164. L_t is well pump-lift in time period t. The factor 2.31 is an engineering parameter representing the height of a column of water that will exert 1 psi pressure. EP is the energy price and has a value of 0.0633 $/kwh. EFF is pump engine efficiency that was assigned a value of 0.50. $WA_{c,t}$ is acre inches of applied water per irrigated acre of crop c in year t.

Gross Pumping capacity per acre per county was estimated as

(4) $$GPC_t = \{4.42*(IWY/IAPW)*(ST_t/IST)**2\}$$

where GPC_t refers to the gross pumping capacity at time period t, IWY is the initial well yield in period 1 measured in gallons per minute, and IAPW is the initial acres served per well in year 1. As before, ST_t is saturated thickness in feet in year t.

Coupling the hydrologic equations of motion governing pumping costs, pump-lift and aquifer storage, within the structure of the dynamic economic optimization model provides the means of accounting for the impact the optimal economic decisions which maximize the present value of agricultural return over the 50 year planning horizon impacts the aquifer over time. A limitation of this modeling framework is that in using average county parameter values the modeling framework ignores the inherent variation in the physical parameters that govern aquifer response. Another important limitation is that ground water withdrawals are spatially heterogeneous within a county. Conventional economic water policy models that impose homogeneity of water use and aquifer response are likely to inaccurately estimate the net social benefit of a given water conservation policy.

Comprehensive Model

As an initial step to overcome the limitations of conventional economic water policy models, this research linked a detailed hydrology model to a dynamic economic model to more accurately capture the relationship between economic activity and aquifer status. Stovall's MODFLOW model (2001) calibrated for the Southern Ogallala Aquifer was used for this purpose. McDonald and Harbaugh (1988) developed the MODFLOW software program and it is the most widely used groundwater simulation program now used. 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. MODFLOW 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.   For a given county, each grid cell contains parameter values for hydraulic conductivity, specific yield, recharge rate, initial saturated thickness, and the proportion of total county ground water withdrawals diverted from the cell in the baseline calibration period (Stovall, 2001). By linking the economic model to the hydrology model, the comprehensive modeling approach is able to maintain the spatial variability in hydrologic response to agricultural groundwater stresses.   Stovall's MODFLOW hydrology model was calibrated for the entire Southern Ogallala Aquifer which spans 25 counties in the Texas Panhandle and six counties in New Mexico. However, detailed economic models were constructed for only 19 of the 31 counties. Economic models were not constructed for six of the Texas counties overlying the Ogallala Aquifer because less than 10 percent of the county land area was above the aquifer and irrigation was minimal in each of these counties. Economic data for the six New Mexico counties was not readily available and no economic model was constructed for these counties. Water use in each county for which an economic model was not constructed was maintained at the initial calibration level.

For purposes of estimating the differences in water use and economic returns generated by the two modeling approaches, the optimal yearly ground water demands as determined by the dynamic economic optimization model over the 50 year planning horizon for each county were input into the MODFLOW hydrology model to determine if there was sufficient ground water supplies at each diversion point to satisfy the ground water demands. The economic model's annual county level water demand estimates were distributed over each hydrology model grid cell in each respective county using a set of weights that sum to one. In a given cell, the weight was the fraction of ground water withdrawals in the cell relative to total county withdrawals in 2000.

The cell level agricultural ground water withdrawal values along with the other input files required by MODFLOW was used to simulate groundwater flow, water table elevation, aquifer storage through time. Groundwater Vistas (GWV) a graphical interface to MODFLOW developed by Environmental Simulations Inc (ESI, 1998) was used to link the hydrology model to the economic model. GWV's matrix calculator feature was used to summarize the output data on cell saturated thickness and water volume and then to subsequently export the data by cell as shape files to ArcMap (ESRI, 2003) for graphical presentation and to Microsoft Excel. Excel was used to calculate annual groundwater withdrawals and pump lift level by county for those cells with a positive saturated thickness at each point in time (cell that were not dry). The annual county estimates for water availability and pump lift derived from the hydrology model were subsequently imported back into the optimization model as parameter values and the dynamic optimization model was used to simulate agricultural net returns, water use, pump lift, and saturated thickness by county over the 50 year planning horizon. The objective of the economic simulation procedure was to derive an improved baseline estimate for agricultural water use and net returns under existing water policy, economic incentives, and irrigation technology after accounting for the spatial heterogeneity of the aquifer.

Results

County Level Comparisons

The results for the two alternative dynamic optimization approaches are presented in this section. The objective function for both approaches maximized the net present value of agricultural crop returns by county over a 50 year planning horizon. Moreover the structure of the constraint set in both modeling approaches is identical and only model parameterization is allowed to vary. The pure economic model is parameterized using average county values, whereas the comprehensive economic model parameter values reflect the inherent variability of the hydrologic characteristics existing with a county. For purposes of brevity, only aggregate data on net economic returns and water use in presented.

Table 1 presents a comparison of per acre average net agricultural return by county for selected years. In the first year per acre net returns are identical because both modeling approaches begin with the same initial condition. However, as the models simulate optimal economic activity through time, estimated per acre net returns begin to diverge between the two approaches because saturated thickness and water withdrawals are not uniform across the individual counties. As shown in Table 1, in most counties average per acre net return is lower in the comprehensive model than in the economic model. By controlling for the aquifer's spatial variability, the comprehensive model was able to account for the increasing percentage of the year 1 irrigated acreage converted to dryland production overtime due to exhaustion of groundwater supplies in specific county sub-areas. This single fundamental difference in the two modeling approaches accounts for the significant differences in estimated per acre net return over time. In Briscoe County, average per acre net return for all cropland (both irrigated and non-irrigated) is 60% less in the last year of the planning horizon when estimated by the comprehensive model. In two other counties, Gaines and Yoakum, average per acre returns are 50 percent when estimated by the comprehensive model.

Somewhat surprisingly, in a few counties the comprehensive model generated minimally higher average per acre net revenue values towards the end of the planning horizon. This seemingly odd outcome is explained by the fact that the equations of motion used in the economic model, were initialized to the average year 1 pump-lift value for all wells pumping in the first year of the planning horizon. The recursive equations of motion only use the initial year average county pump-lift value to calculate average year 2 county pump-lift value. The change in saturated thickness from year 1 to year 2 is calculated as the sum of total county recharge plus net lateral inflow less groundwater withdrawals occurring year 1. In subsequent years, the recursive equations of motion calculate current average year pump-lift in each county, as the sum of the prior year's average pump-lift, at the beginning of the year, plus the change in county saturated thickness that occurred in the prior year. In calculating year 3 pump-lift only year 2 beginning pump-lift and the year 2 change in saturated thickness are needed. Hence, by construction, when the equations of motion are used to determine average county pump-lift values, pump-lifts will annually decrease as long as county withdrawals exceed recharge. Thus, it is possible for the average pump-lift of wells continuing to pump within a county to decrease, if the wells going dry had greater than average pump-lifts, even though the average saturated thickness of the aquifer within the county decreased. As shown in Table 1, per acre net returns are slightly higher in six of the nineteen counties when using the comprehensive model due to this phenomenon. The comprehensive model estimated average county pump-lift as the average of the cells pumping at each point in time. This unanticipated finding again highlights the importance of accounting for spatial heterogeneity in constructing water policy models. In two counties, Bailey and Hale, per acre return is nearly 10 percent higher in the last year of the planning horizon when estimated by the comprehensive model. Though not reported, over the entire 50 year planning horizon, the present value of net agricultural returns to each county was only minimally larger in one county as estimated by the comprehensive model relative to the economic model (NPV for Hale County was 1% larger).

Table 2 provides the county water use level estimates forthcoming from the two modeling approaches for selected years. For all counties the comprehensive model estimates of water use over time is less for the comprehensive model. Generally speaking the higher the greater the difference in the two water use estimates the greater the difference in the previously discussed per acre net return estimates. The economic model's overstatement of water use is attributable the economic model's inability to account for the aquifer's spatial heterogeneity.

Table 3 presents a comparison of irrigated acreage and average per acre irrigation application rates for the two modeling approaches. The percentage share of all cropland irrigated declines more rapidly when using the comprehensive modeling approach, than when using the economic modeling approach. For example, irrigated acreage in Gaines County in 2029 (twenty-five years into the planning horizon) remains at initial year 1 level of 61.4% before declining to 46% by the end of the 50 year planning period (year 2053). However, in comprehensive model only 41.4% of all cropland is irrigated after 25 years, and only 16.9% of all cropland is irrigated at the end of the 50-year planning period. The rapid decrease in irrigated acreage over time largely explains the smaller annual per acre average net agricultural return estimates provided by the comprehensive modeling framework. As shown in table 3, average per acre water application rates tend to be fairly constant over time. This suggests that it is generally more profitable to take irrigated acreage out of production than reduce the irrigation application rate or irrigated acreage.

Table 4 presents a comparison of average county pump-lift estimated by the two modeling approaches for selected years. In the base year (year 1), estimated lifts are equal for both approaches since both models are started with the same initial conditions. However, at the end of the 50 year planning horizon, significant differences exit between the estimated average pump-lift values. Average pump-lift estimates for the counties of Castro, Crosby, Gaines, Floyd, Hale, Lamb and Lubbock are at least 60 feet greater as estimated by the economic model than the comprehensive model. The cause of this phenomenon was previously discussed and occurred because the economic modeling approach does not accurately account for spatial heterogeneity.

Detailed Analysis: Gaines County

The primary advantage of the comprehensive model approach is the ability to maintain the spatial differences in hydrologic response to economically motivated ground water withdrawals within a county. The number of cells in the grid that go dry after each simulation period is indicative of the percentage of areas that remain irrigated through time. Excluding Briscoe, Hockley, Lubbock and Swisher counties, at least 50 percent of the wells pumping in year 1 are still pumping at the end of the 50-year planning horizon. And in five counties, Parmer, Lamb, Hale, Castro and Bailey, more than 90 percent of cells with withdrawals in year1 are still providing groundwater in year 50. However, in four counties, Briscoe, Hockley, Lubbock and Swisher, as over 60 percent of the wells that were pumping in year 1 were dry by the end of the planning horizon. Overall, sixty-seven percent of the cells providing ground water supplies in year 1 were still active at the end of the planning horizon. Gaines County is used to more fully illustrate the differences in the economic and hydrologic estimates resulting from the two alternative modeling approaches.

Figures1 and 2 graphically portray the areas of Gaines County having saturated thickness (stored water supplies) at the beginning and end of the planning horizon. In figures 1 and 2 the black cells designate areas of the county with saturated thickness, and the white cells areas without saturated thickness. At the end of the 50-year simulation period, nearly 50 percent of the county land base is without ground water supplies.

Figure 3 presents the net return to all agricultural cropland (both irrigated and non-irrigated) in Gaines county as determined by the two modeling approaches. Over the first five years of the planning horizon, average per acre net returns increase under both modeling approaches parallel each other as producers continue their historic shift away from less profitable year 1 crop mix to more profitable cropping alternatives. However, beginning in the six year average per acre return begins to diverge, with the comprehensive estimate being the lower of the two return estimates. The divergence is due to reductions in irrigated acreage and water application levels though time. The traditional economic modeling approach use of average values, in combination with the traditional approach's inability to account for the spatial variability in aquifer water supplies results in the traditional economic approaches higher per acre net economic return estimates over time.

The divergence between the estimates for Gaines County percentage of acreage irrigated as a share of total cropland is shown in figure 4. In the economic model, the percentage share of irrigated acreage remains fixed for the first 44 years, at the year 1 level of 61.1 percent, before beginning a decline to a share of 45.9 percent at the end of the planning period. In contrast, the comprehensive model predicts the county percentage share will begin to decline after only 14 years, and only 16.86 percent of all acreage will be irrigated at the end of the 50-year planning horizon. Referring back to figures 1 and 2, it is clear that significant portions of the county can no longer support irrigated agriculture by the end of the planning horizon. The reduction is disproportionate to the decrease in cells with saturated thickness because not all cells with saturated thickness were pumping groundwater in year 1, the calibrated baseline year, because the land above the aquifer in some areas is unsuited for irrigated agriculture.

Figure 5 reveals that even though the comprehensive model's estimate of the percentage share of cropland irrigated relative to the economic model's estimate did not begin to diverge till year 14, per acre water application rates began to diverge in year 6 with the comprehensive model providing the lower application rates. This inability of the economic model to account for declining application rates through time resulted in the economic model's larger estimates for per acre net return over time.

Figure 6 compares the annual agricultural water use estimates provided by the two alternative modeling approaches through time. Beginning in year six the annual water use estimates begin to diverge. The much higher water use rates provided by the economic model are an artifact of using average values to estimate drawdown rates. The averages used by the economic model mask the reality that significant areas of the county are going dry through time and irrigated production could no longer be supported in these areas. The economic modeling approach only reduces groundwater use when the marginal value of the water applied to a given crop no longer exceeds its pumping cost, or marginal cost. Thus, under the economic model formulation, as average pump-lifts increase, marginal application cost will increase, and water will be applied up to the point where marginal value is equal to marginal cost, when in reality there may be no saturated thickness below a given parcel of land to support the groundwater withdrawal. This further highlights the need account for spatial heterogeneity in developing water policy planning models

Figure 7 compares aquifer saturated thickness estimates generated by the two modeling approaches for the portion of the aquifer below Gaines County through time. Given the proceeding discussion the results are as expected. The economic model shows a much more rapid depletion rate than the comprehensive model. This is expected due to the fact that the economic model overestimated withdrawals over time.

The change in average well pump-lift through time is presented in Figure 8 for the two modeling approaches. After year 10 the economic model consistently estimates higher average annual pump-lifts than the comprehensive model. The higher estimated lifts associated with the economic model occur because the economic model's calculation procedure does not adjust the annual pump-lift estimate to account for high pump lift well that go dry overtime. Moreover, the economic model uses an average recharge rate for an entire county, whereas recharge rates can and do vary over a county. Generally speaking, those areas of Gaines County that are still actively providing irrigation supplies at the end of the 50 year planning horizon have recharge rates above the county average.

Conclusion

The compressive modeling approach uses a temporally and spatially disaggregated analytic framework. A modeling framework of this type will provide water policy analysts with a superior planning tool and means to evaluate the benefits and costs of water policies designed to address long-run economic sustainability issues. Failure to account for spatial heterogeneity, overstated expected agricultural net returns and water use over a 50 year planning horizon relative to the comprehensive modeling approach that linked a detailed hydrology model to the dynamic economic model. 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 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. Such models can also assist policy makers in addressing issues of intergenerational equity and distribution of groundwater resources over sectors through time. In general, the comprehensive approach provides a superior means to examine the impacts of alternative demand and/or supply management strategies and aid policy makers towards better economic decision making.

A limitation of comprehensive model is that the current version of the model does not address the issue of variability in agricultural land practices. Due to data limitation, the results presented were derived under the assumption that irrigated land practices within a county were homogeneous. However, land management practices and cropping patterns can significantly vary within a county. Micro level data on land management practices would enhance the value of the modeling approach by enabling policy makers to target specific areas with tailor made policies aimed at water conservation. Another limitation is that the analysis held technology fixed over the 50 year planning horizon.

References

ArcMap, Environmental Systems Research Institute, ESRI, 2003

Arabiyat. S T., "Agricultural Sustainability in the Texas High Plains: The role of Advanced Irrigation Systems and Biotechnology", Unpublished Masters Thesis, Department of Agricultural and Applied Economics, Texas Tech University,1998.

Ground Water Vistas, Environmental Solutions Inc, 1998.

High Plains Underground Water Conservation District, Lubbock, Texas, 2003. http://www.hpwd.com

Johnson Jeffrey W., "Water Conservation Policy Alternatives for the Southern Portion of the Ogallala Aquifer", Unpublished PhD dissertation, Department of Agricultural and Applied Economics, Texas Tech University (2003)

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

Stovall Jeff N., "Groundwater Modeling for the Southern High Plains", Unpublished Ph.D Dissertation, Department of Civil Engineering, Texas Tech University, 2001

Texas Agricultural Statistics Service, http://www.nass.usda.gov:81/ipedb/, 2004.

Water for Texas, January 2002, Texas Water Development Board, Austin, Texas, 78711

Table 1. Selected Year per Acre Net Return (Dollars) by County: Pure Economic Model versus Comprehensive Model[1]

County	Economic Model 2004	Economic Model 2029	Economic Model 2053	Comprehensive Model 2004	Comprehensive Model 2029	Comprehensive Model 2053	Difference[2] 2029	Difference[2] 2053
Bailey	-1.34	32.91	32.86	-1.34	34.86	37.29	-1.95	-4.43
Briscoe	49.16	85.74	85.51	49.16	67.65	34.39	18.09	51.12
Castro	0.70	25.49	28.76	0.70	26.78	30.83	-1.29	-2.07
Cochran	24.01	61.22	47.53	24.01	44.19	30.59	17.03	16.94
Crosby	9.83	35.44	31.64	9.83	32.77	31.81	2.67	-0.17
Dawson	-37.21	8.38	12.09	-37.30	6.99	10.49	1.39	1.60
Deaf Smith	-12.16	23.80	17.15	-12.18	21.34	16.90	2.46	0.25
Floyd	36.64	45.59	29.35	36.64	46.02	30.97	-0.43	-1.62
Gaines	61.82	102.19	65.21	61.73	62.08	31.45	40.11	33.76
Garza	7.07	46.67	49.74	6.75	35.17	36.88	11.50	12.86
Hale	65.72	33.77	31.78	65.74	38.03	35.45	-4.26	-3.67
Hockley	3.83	23.94	21.54	3.83	20.51	21.09	3.43	0.45
Lamb	13.30	38.41	31.80	13.30	38.56	34.00	-0.15	-2.20
Lubbock	30.48	28.05	20.78	30.48	18.74	17.54	9.31	3.24
Lynn	9.12	52.94	56.47	9.12	40.06	40.94	12.88	15.53
Parmer	-24.84	21.64	25.62	-24.84	21.89	25.65	-0.25	-0.03
Swisher	46.14	63.03	43.21	46.14	33.26	31.23	29.77	11.98
Terry	52.53	99.98	77.00	52.33	50.98	40.20	49.00	36.80
Yoakum	75.90	126.64	108.76	75.90	70.68	54.75	55.96	54.01

[1] Average per acre Net Return for all acreage planted in year 1 (average return to all irrigated and non-irrigated year 1 acreage)

[2] Average per acre return economic model less average per acre return comprehensive model

Table 2. Acre-Feet Ground Water Withdrawals by County for Selected Years: Pure Economic Model versus Comprehensive Model

	Economic Model			Comprehensive Model			Difference[1]	
County	2004	2029	2053	2004	2029	2053	2029	2053
Bailey	150,799	165,244	166,432	150,799	160,054	155,705	5,190	10,728
Briscoe	65,176	73,855	74,298	65,176	38,404	1,486	35,451	72,812
Castro	448,948	103,619	134,106	448,948	88,496	111,043	15,124	23,063
Cochran	168,270	175,223	73,468	168,270	56,508	22,062	118,714	51,406
Crosby	208,995	210,713	211,467	208,995	154,835	122,119	55,877	89,349
Dawson	83,446	85,643	86,121	83,446	52,439	48,057	33,203	38,063
Deaf Smith	221,535	361,893	164,668	221,535	271,001	72,372	90,892	92,296
Floyd	355,324	361,374	76,905	355,324	269,539	54,162	91,835	22,742
Gaines	464,097	411,289	226,145	464,097	207,014	83,153	204,275	142,992
Garza	18,822	18,956	19,023	18,822	8,482	7,859	10,474	11,163
Hale	603,356	139,793	86,186	603,356	130,347	79,129	9,445	7,057
Hockley	315,321	271,985	89,747	315,321	74,235	22,862	197,750	66,885
Lamb	337,433	305,787	115,392	337,433	281,892	97,238	23,895	18,154
Lubbock	407,090	232,040	102,693	407,090	69,171	30,241	162,869	72,452
Lynn	128,338	131,778	132,568	128,338	61,219	49,799	70,559	82,770
Parmer	343,258	27,778	2,051	343,258	27,653	2,042	125	9
Swisher	236,395	234,192	98,839	236,395	37,609	14,193	196,583	84,647
Terry	271,795	236,320	138,226	271,795	73,293	37,052	163,027	101,174
Yoakum	162,496	176,691	127,757	162,496	67,197	39,318	109,495	88,439

[1] Selected year acre-feet water use economic model less acre-feet use comprehensive model

Table 3. Percentage County Irrigated Acreage and Average Water Application: Economic Model versus Comprehensive Model

	Economic Model						Comprehensive Model					
	2004		2029		2053		2004		2029		2053	
County	IA[1]	AW[2]	IA	AW	IA	AW	IA	AW	IA	AW	IA	AW
Bailey	39.5	21.0	39.5	23.0	39.5	23.2	39.5	21.0	39.5	22.3	39.5	21.7
Briscoe	32.8	25.0	32.8	28.4	32.8	28.5	32.8	25.0	20.2	24.0	1.9	10.0
Castro	74.4	19.4	15.1	22.1	17.9	24.1	74.4	19.4	13.9	20.5	14.9	24.0
Cochran	40.8	23.3	40.8	24.2	16.1	25.8	40.8	23.3	12.8	25.0	8.8	14.1
Crosby	54.8	16.8	54.8	16.9	54.8	17.0	54.8	16.8	42.7	16.0	33.4	16.1
Dawson	12.1	21.3	12.1	21.9	12.1	22.0	12.1	21.3	8.0	20.3	7.3	20.4
Deaf Smith	45.1	17.3	45.1	28.2	20.5	28.3	45.1	17.3	35.1	27.1	9.1	28.1
Floyd	59.1	21.5	59.1	21.9	12.8	21.6	59.1	21.5	45.0	21.5	9.0	21.6
Gaines	61.1	20.5	61.1	18.2	46.0	13.3	61.1	20.5	41.4	13.5	16.9	13.3
Garza	24.1	18.3	24.1	18.4	24.1	18.5	24.1	18.3	13.4	14.8	12.4	14.9
Hale	83.9	21.4	19.7	21.1	11.8	21.7	83.9	21.4	18.4	21.1	10.9	21.7
Hockley	45.3	22.6	39.0	22.6	12.8	22.7	45.3	22.6	10.7	22.6	3.3	22.6
Lamb	69.5	16.6	69.5	15.1	26.2	15.1	69.5	16.6	64.7	14.9	21.9	15.2
Lubbock	60.6	22.5	36.4	21.3	15.7	21.9	60.6	22.5	11.5	20.1	4.6	21.9
Lynn	21.9	19.0	21.9	19.5	21.9	19.6	21.9	19.0	12.6	15.7	10.1	16.0
Parmer	68.8	17.6	5.5	17.9	0.4	18.4	68.8	17.6	5.5	17.8	0.4	18.3
Swisher	48.2	20.3	45.2	21.4	18.8	21.7	48.2	20.3	7.9	19.7	2.8	21.3
Terry	49.5	18.4	49.5	16.0	42.3	11.0	49.5	18.4	21.8	11.3	11.4	10.9
Yoakum	49.2	19.1	49.2	20.7	49.2	15.0	49.2	19.1	26.8	14.5	15.6	14.5

[1] Percent of all year 1 crop acreage (irrigated and dryland) irrigated.

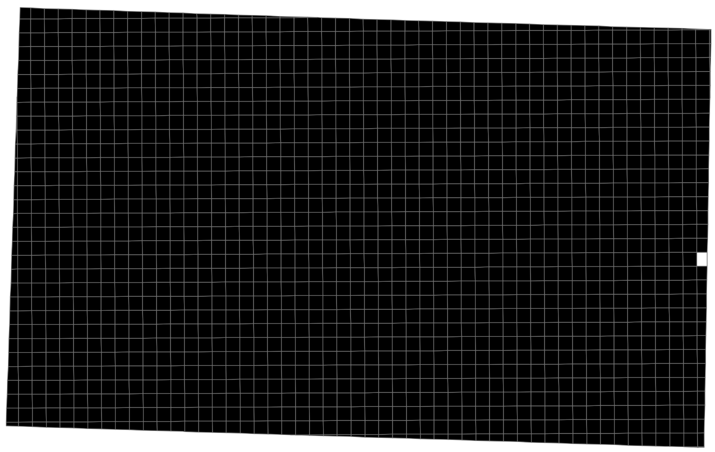
[2] Acre-inches applied irrigation water per irrigated acre.

Table 4. Selected Year Pump- Lifts (Feet) for Wells Pumping Water: Economic Model versus Comprehensive Model

	Economic Model			Comprehensive Model			Difference[1]		
County	2004	2029	2053	2004	2029	2053	2004	2029	2053
Bailey	108.00	123.03	138.09	108.00	110.79	111.15	0.00	12.25	26.94
Briscoe	131.00	143.54	156.06	131.00	143.02	156.06	0.00	0.52	0.00
Castro	198.00	251.41	260.22	198.00	224.43	230.05	0.00	26.98	30.16
Cochran	93.00	110.79	118.66	93.00	95.56	79.96	0.00	15.23	38.71
Crosby	251.00	283.04	313.74	251.00	262.02	254.98	0.00	21.02	58.75
Dawson	60.50	59.76	59.10	60.50	62.57	61.77	0.00	-2.81	-2.67
Deaf Smith	226.00	248.97	270.69	226.00	244.95	244.80	0.00	4.02	25.89
Floyd	240.50	291.58	307.46	240.50	260.37	241.17	0.00	31.21	66.29
Gaines	108.00	142.27	166.06	108.00	123.79	119.73	0.00	18.48	46.33
Garza	94.00	95.37	96.71	94.00	93.98	92.40	0.00	1.39	4.31
Hale	189.00	259.11	263.37	189.00	197.10	178.33	0.00	62.01	85.04
Hockley	131.00	162.24	169.51	131.00	140.86	125.55	0.00	21.38	43.96
Lamb	152.00	195.95	219.94	152.00	163.22	156.68	0.00	32.74	63.26
Lubbock	133.00	183.71	189.10	133.00	147.39	127.09	0.00	36.33	62.01
Lynn	57.00	54.51	52.18	57.00	61.74	58.85	0.00	-7.24	-6.67
Parmer	303.00	314.45	302.28	303.00	302.35	290.71	0.00	12.10	11.57
Swisher	158.00	182.03	188.77	158.00	166.99	148.67	0.00	15.05	40.09
Terry	95.00	117.70	126.43	95.00	104.21	96.17	0.00	13.49	30.25
Yoakum	91.00	110.30	127.53	91.00	102.30	96.70	0.00	8.00	30.84

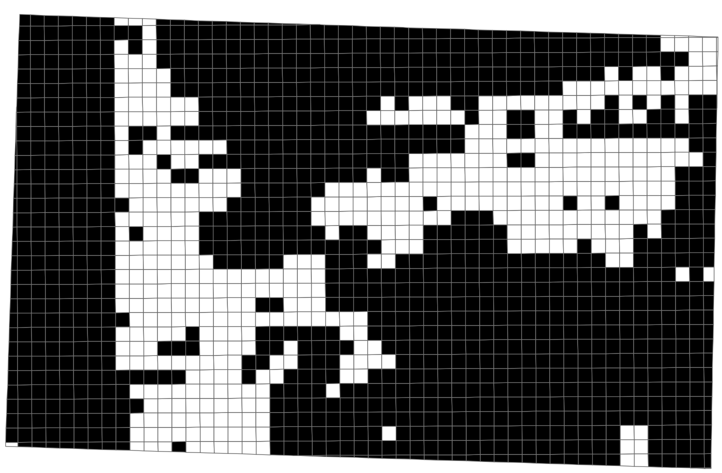
[1] Selected year average well pump-lift economic model less average well pump-lift comprehensive model

Figure 1: Areas of Gaines County with Saturated Thickness in year 2004



Note: Black areas designate cells with saturated thickness, and white areas represent dry cells.

Figure 2: Areas of Gaines County with Saturated Thickness in year 2053



Note: Black areas designate cells with saturated thickness, and white areas represent dry cells.

Figure 3: Gaines County Total Crop Net Revenue: Economic versus Comprehensive Model

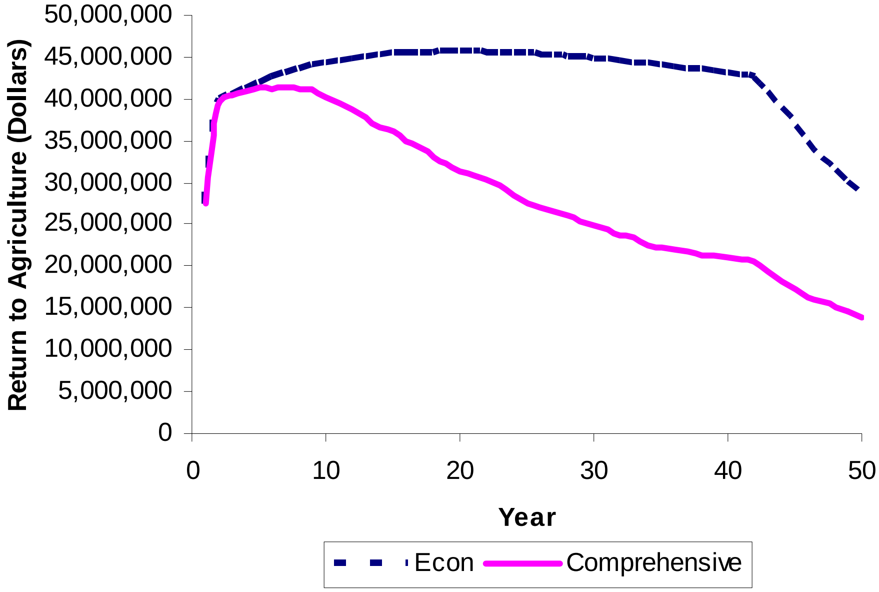


Figure 4: Gaines County Percentage Cropland under Irrigation: Economic versus Comprehensive Model

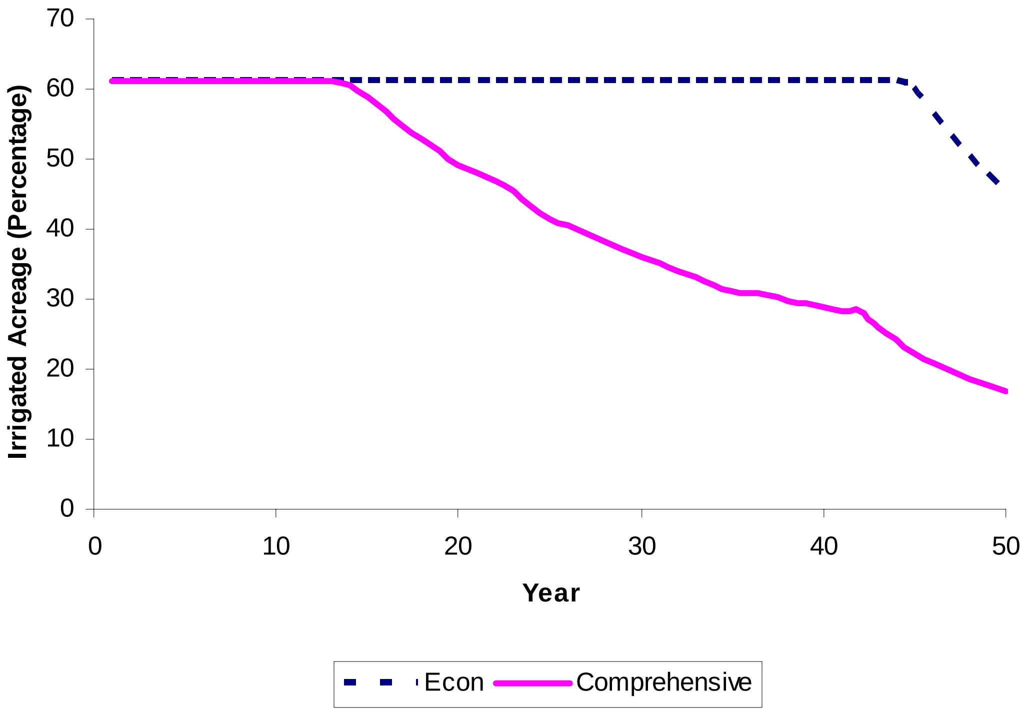


Figure 5: Acre Inches Applied Water per Irrigated Acre in Gaines County: Economic versus Comprehensive Model

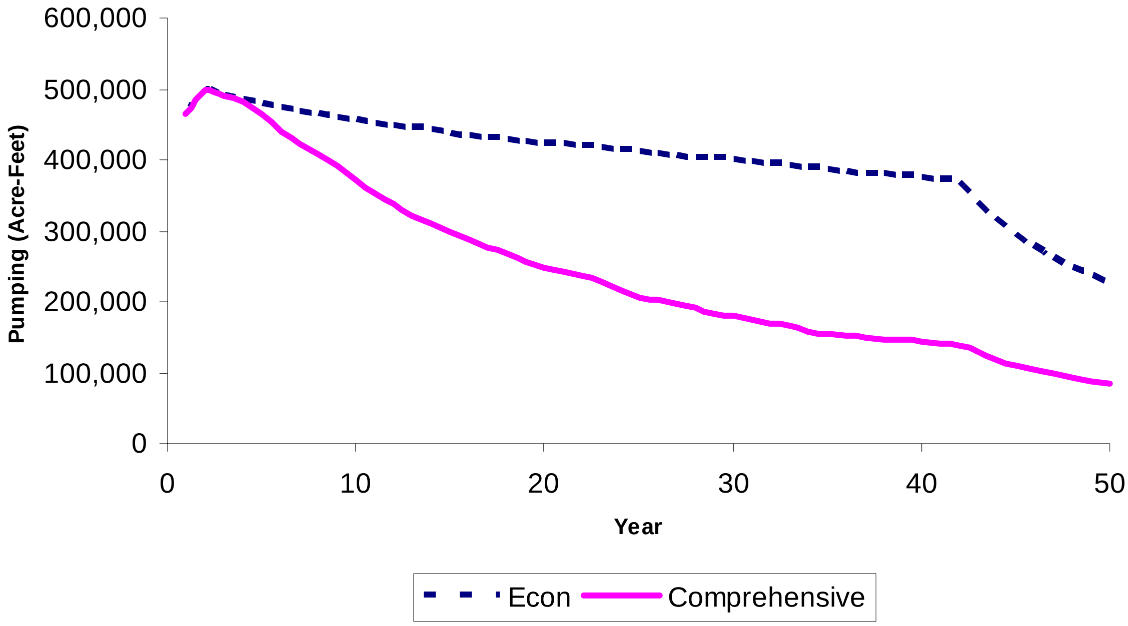


Figure 6: Gaines County Annual Groundwater Use: Economic versus Comprehensive Model

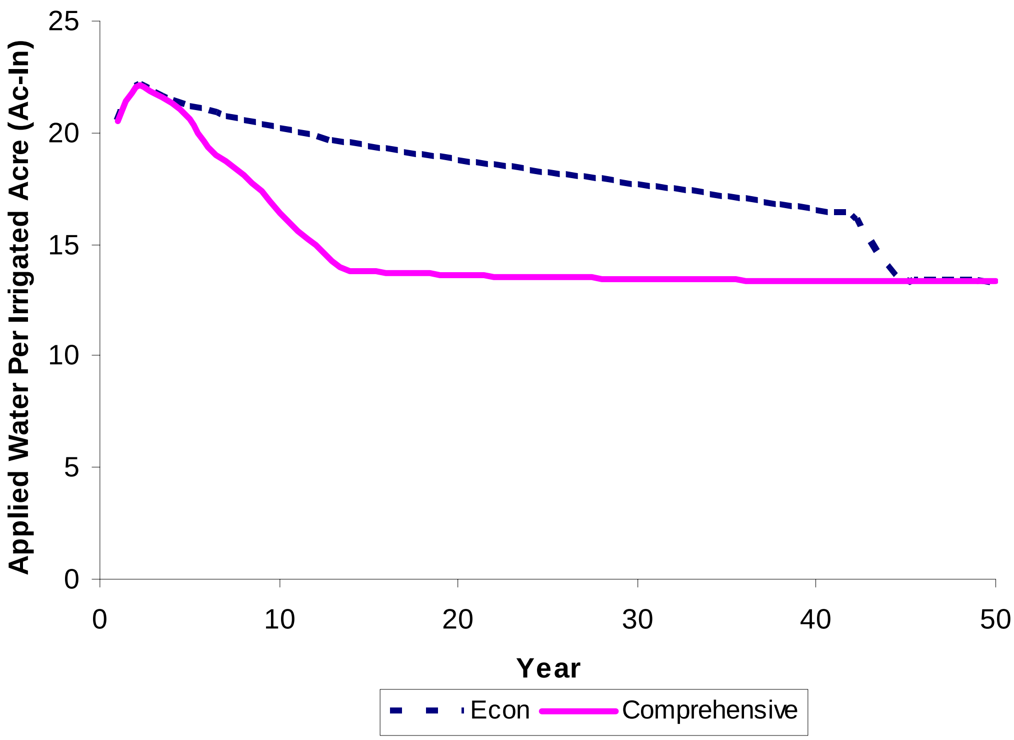


Figure 7: Gaines County Saturated Thickness (Feet): Economic versus Comprehensive Model

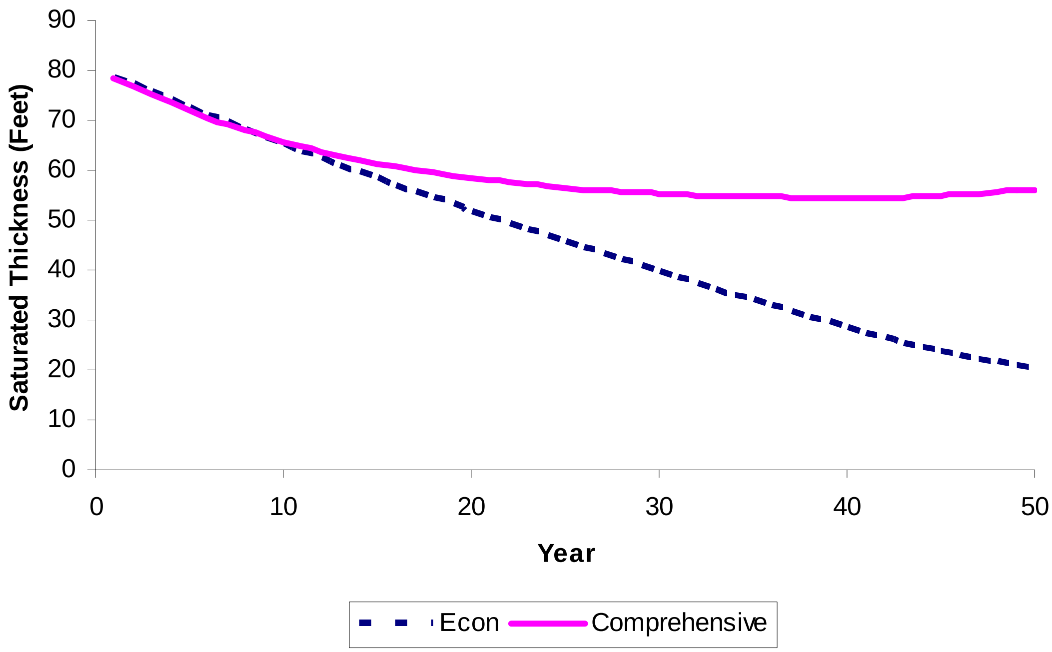


Figure 8. Gaines County Pump Lift (Feet) for pumping wells: Economic versus Comprehensive Model