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Introduction

Since the late 1800's, irrigated agriculture has played a vital role in the development and growth of the Great Plains Region of the United States. The primary source of water for irrigation in this region is the Ogallala Aquifer, which encompasses 174,000 square miles and underlies parts of eight states: Texas, New Mexico, Oklahoma, Colorado, Kansas, Nebraska, South Dakota, and Wyoming (Alley, Riley, and Franke, 1999). In the Great Plains Region, the water pumped from the Ogallala Aquifer accounts for approximately 65% of the total water used for irrigation in the U.S. annually (High Plains Water District #1, 2004). The Southern portion of the Ogallala Aquifer is considered exhaustible due to the relatively low level of recharge when compared to the quantities of water pumped annually for agricultural production of cotton, corn, grain sorghum, wheat, and peanuts.

The Great Plains region produces approximately 45% of the national production of wheat, 25% of the national production of corn, over 88% of the national production of grain sorghum, and 32% of the national production of cotton (NASS, 1999). Another important agricultural activity in the Great Plains is the cattle feeding industry, composed of feedlots and beef packing plants, where over 15 million head of cattle, or 18% of the national production, is produced annually (Dennehy, 2002).

Average precipitation in the Southern portion of the Great Plains ranges from 15 to 20 inches per year; however, a minute amount of precipitation contributes to the recharge of the aquifer due to the high evapotranspiration. Ninety percent of the recharge in the aquifer is percolated through the soil through small playa lakes that dot the landscape from Texas to Nebraska (Alley, Riley, and Franke, 1999). Sources vary on the exact amount of recharge in the Southern portion of the Ogallala Aquifer, but many agree on a range from half an inch to several inches per year per surface acre (High Plains Water District #1, 2004).

In the early 1950's, approximately 480 million cubic feet of groundwater per day was used for irrigation from the Ogallala Aquifer. By 1980, that amount had increased to 2,150 million cubic feet per day (Alley, Reilly and Franke, 1999). Water table levels in the Ogallala currently decline in a range from approximately half a foot to several feet annually. The effect of recharge when compared to the rate of depletion is insignificant (Birkenfeld, 2003). Many believe that a decline in the aquifer toward economic depletion will likely have a dramatic detrimental impact on the irrigated agriculture dependent regional economy of the Great Plains.

Water conservation policies may effectively extend the economic life of the Ogallala Aquifer in the Southern High Plains of Texas and Eastern New Mexico and maintain the viability of a regional economy dependent on agriculture. This study evaluates water conservation policies which limit drawdown of the aquifer over a sixty year planning horizon.

Because the majority of the study area is in Texas, the addressed water conservation policy alternatives find their basis and are most applicable to the Texas counties of the study area. The goal of the policy alternatives is allowing agricultural irrigation and water for other uses to be available further into the future than would result under current water extraction practices.

The policy alternatives considered and compared in this study include: 1) compensating producers for decreasing water usage to 0% drawdown relative to the amount that would have otherwise been used over sixty years through a water conservation reserve program, 2) limiting water usage to limit drawdown to 50% of the water that would be used in the absence of a policy over sixty years, 3) limiting water usage to limit drawdown to 75% of what would be remaining in the aquifer without a policy over sixty years, and 4) limiting water usage to an annual extraction quota to achieve 50% drawdown relative to the amount of water that would have been used over the sixty year planning horizon. The first alternative considered is similar to the Federal Conservation Reserve Program (CRP) enacted for soil conservation, but with a goal of water conservation. The second, third, and fourth alternatives are directly linked to Senate Bills 1 and 2 passed by the Texas Legislature in 1997 and 2001, respectively. As discussed previously, Senate Bills 1 and 2 gave UWCDs the right to regulate water usage.

Comparisons were conducted between the policy alternatives to weigh the costs and benefits to producers and society under the contrasting alternatives. The baseline, the solution which provides the optimal amount of water to use in the absence of a water use constraint, was compared to the 0% drawdown (CRP) alternative as well as the 50% and 75% total drawdown policies. Additionally, the 50% total alternative was compared to the 50% annual quota restriction alternative in order to provide insight to policy makers to help decide whether the short term annual 50% restriction or the 50% total drawdown restriction leads to the most efficient outcome. These comparisons illustrate the marginal effects of water usage under the different alternatives.

Study Area

As the decline of the aquifer becomes a timely topic in state legislatures across the Great Plains, it is important to sub-divide the aquifer into regions where more specialized and accurate information can be analyzed. This study focuses primarily on the Southern Sub-Region which includes the Southern portion of the Texas Panhandle and Eastern Plains of New Mexico. This region, lying on the 100th meridian, is the second largest water use area, behind Nebraska, of the Ogallala Aquifer, accounting for approximately 12% of annual extraction (National Research Council, 1996). Specifically, the counties were: Andrews, Bailey, Borden, Cochran, Crosby, Dawson, Dickens, Floyd, Gaines, Garza, Glasscock, Hale, Hockley, Howard, Lamb, Lubbock, Lynn, Martin, Midland, Motley, Terry, and Yoakum in Texas, and Lea and Roosevelt in New Mexico.

Objectives

The primary objective of this study was to analyze and evaluate the impacts of selected water conservation policy alternatives on the Ogallala Aquifer underlying the Southern High Plains of Texas and Eastern New Mexico for the purposes of identifying which alternative or alternatives most effectively achieve conservation of the aquifer and keep the heavily agriculturally dependent economy viable. The specific objectives were to:

1. Determine the characteristics of water conservation policy alternatives which could extend the economic life of the aquifer, and
2. Evaluate the economic life of the aquifer across the region under different water conservation alternatives for a sixty year planning horizon.

Model Specification

The framework of the optimization model used in this study was originally developed by Feng (1992) and has been expanded and modified by Terrell (1998), Johnson (2003), and Das (2004). The objective of the this study's county level optimization models is to maximize net present value of net returns to land, management, groundwater, and irrigation systems over a sixty year planning horizon for a given county as a whole.
The objective function is:

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

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

$$NR_t = \sum_i \sum_k \Theta_{ikt} \{ P_i Y_{ikt} [WA_{ikt}, (WP_{ikt})] - C_{ik} (WP_{ikt}, X_t, ST_t)\}. \qquad (2)$$

Where: i represents crops grown; k represents irrigation technologies used; Θ_{ikt} is the percentage of crop i produced using irrigation technology k in time t, P_i is the output price of crop i, WA_{ikt} and WP_{ikt} are per acre irrigation water applied and water pumped per acre respectively. $Y_{ikt}[\cdot]$ is the per acre yield production function, C_{ikt} represents the costs per acre, X_t is pump lift at time t, ST_t represents the saturated thickness of the aquifer at time t.
The constraints of the model are:

$$ST_{t+1} = ST_t - [(\sum_i \sum_k \Theta_{ikt} * WP_{ikt}) - R]A/s, \qquad (3)$$
$$X_{t+1} = X_t + [(\sum_i \sum_k \Theta_{ikt} * WP_{ikt}) - R] A/s, \qquad (4)$$
$$GPC_t = (ST_t/IST)^2 * (4.42*WY/AW), \qquad (5)$$
$$WT_t = \sum_i \sum_k \Theta_{ikt} * WP_{ikt}, \qquad (6)$$
$$WT_t \leq GPC_t \qquad (7)$$
$$PC_{ikt} = \{[EF(X_t + 2.31*PSI)EP]/EFF\}*WP_{ikt}, \qquad (8)$$
$$C_{ikt} = VC_{ik} + PC_{ikt} + HC_{ikt} + MC_k + DP_k + LC_k \qquad (9)$$
$$\sum_i \sum_k \Theta_{ikt} \leq 1 \text{ for all t}, \qquad (10)$$
$$\Theta_{ikt} \geq (2/3)\, \Theta_{ikt-1}, \qquad (11)$$
$$\Theta_{ikt} \geq 0. \qquad (12)$$

Equations (3) and (4) represent the two equations of motion included in the model which update the two state variables, saturated thickness and pumping lift, ST_t and X_t respectively where R is the annual recharge rate in feet, A is the percentage of irrigated acres expressed as the initial number of irrigated acres in the county divided by the area of the county overlying the aquifer, and s is the specific yield of the aquifer.

Constraints (5), (6) and (7) are the water application and water pumping capacity constraints respectively. In equation (5), GPC represents gross pumping capacity, IST represents the initial saturated thickness of the aquifer and WY represents the average initial well yield for the county. Equation (6) represents the total amount of water pumped per acre, WT_t, as the sum of water pumped on each crop. Constraint (7) requires WT_t to be less than or equal to GPC.

Equations (8) and (9) represent the cost functions in the model. In Equation (8), PC_{cit} represents the cost of pumping, EF represents the energy use factor for electricity, EP is the price of energy, EFF represents pump efficiency, and 2.31 feet is the height of a column of water that will exert a pressure of 1 pound per square inch. Equation (9) expresses the cost of production, C_{ikt} in terms of VC_{ik}, the variable cost of production per acre, $HC_{ikt,}$ the harvest cost per acre, MC_k, the irrigation system maintenance cost per acre, DP_k, the per acre depreciation of the irrigation system per year, and LC_k, the cost of labor per acre for the irrigation system.

Equation (10) limits the sum of all acres of crops i produced by irrigation systems k for time period t to be less than or equal to 1. Equation (11) is a constraint placed in the model to limit the annual shift to a 33% change from the previous year's acreage. Equation (12) is a non-negativity constraint to assure all decision variables in the model take on positive values.

Data Collection

Specific data was compiled for each county within the study region for both Texas and New Mexico. The county specific data included a five year average of planted acreage of cotton, corn, grain sorghum, wheat and peanuts; total acreage under conventional furrow, low application spray application (LEPA) and dryland. Operating costs associated with the most commonly used crop production practices was also collected for specific crops, including fertilizer, herbicide, seed, insecticide, fuel, irrigation technology maintenance, irrigation, labor, and harvesting costs. Finally, hydrologic data was collected, including the area of each county overlying the aquifer, average recharge, total crop acres per irrigation well, average saturated thickness of the aquifer, initial well yield, and average pump lift.

Hydrologic Data: The amount of annual recharge in the Southern Ogallala is not known, and most estimates are considered controversial at best. For the purposes of this study, a recharge estimate by Stovall (2001) using Texas Water Development Board data was used. Stovall separated recharge into two categories, primary and secondary. Primary recharge values were available for each square mile in the study area. However, there were fewer values for secondary recharge. Therefore, the recharge value used was average primary recharge by county plus a weighted secondary county recharge value to account for the differences in data availability between the two recharge estimates. There were no values of secondary recharge for Andrews, Midland, and Glasscock Counties. Therefore, Martin County secondary values were used for Midland and Andrews Counties and Howard County values for Glasscock County. Additionally, recharge values were unavailable for Lea and Roosevelt Counties in NM. For this reason Gaines County, TX values were used for Lea County and Bailey County, TX values were used for Roosevelt County.

Saturated thickness and pump lift by county were calculated from the TWDB groundwater database reports for the most recent year's data. Saturated thickness was calculated by subtracting the depth to water from the depth of the well. Pump lift was calculated as the depth from the surface to the water level. An estimated specific yield of 0.15 was used for the entire study area and the initial well yield by county was estimated using the Analytical Study of the Ogallala Aquifer in various counties (Texas Water Development Board, 1976). Initial acres served per well was calculated from the TWDB Survey of Irrigation (2000) as the number of acres irrigated with groundwater divided by the number of wells in the county.

Acreages: General county acreages including area of the county were obtained from the 2000 U.S. Estimating county acreages by crop was a two step process: 1) dryland and irrigated county planted acres by crop were obtained from the Farm Service Agency (FSA) for 1999-2003, 2) FSA planted acres were converted to harvested acres using the ratio of planted to harvested acres for the same crops and systems for 1999-2003 from the National Agricultural Statistics Service (NASS).

In order to allocate irrigated acres between furrow and LEPA, the TWDB Survey of Irrigation (2000) was used to obtain the total acres irrigated by groundwater and by LEPA for each county in the study region. Assuming only two systems, furrow and LEPA, allowed the subtraction of acres irrigated with sprinkler (LEPA) from total groundwater irrigated acres to obtain the percent of acres under furrow and LEPA for each county.

Finally, the percent irrigated by each system was multiplied by the number of irrigated acres of each crop in a county to estimate county acreages by crop and system with the exception of peanuts and corn due to the fact that no dryland corn and only LEPA peanuts are grown.

Production Functions: The crop simulation software CROPMAN, discussed previously, was used to estimate county production function parameters by crop and system. The most prevalent soil types along with the weather data from the closest weather stations were used for each county. CROPMAN data files for New Mexico counties were unavailable; therefore Gaines County and Bailey County productions functions were used for Lea and Roosevelt Counties, respectively. Yields were obtained from CROPMAN for LEPA (95% efficiency) and furrow (60% efficiency) for varying water application rates. Regressions for each crop and system were then estimated in Microsoft Excel where Y was calculated as the CROPMAN yield minus the actual NASS 1999-2003 average dryland yield, X was water application rate, and X^2 was water application rate squared. The regression was estimated setting the intercept to zero, then adding back the dryland intercept.

Commodity Prices: Prices for wheat, corn, and sorghum were collected from the Agricultural Marketing Service (AMS). The prices were 1999-2003 AMS quotes for South of Line from Plainview to Muleshoe. Due to the fact that the price of cotton for the same five year period was below the marketing loan price, a price equal to the loan price plus coupled government payments ($.57) was used in place of the AMS price. Additionally, AMS does not include peanut prices and therefore the 1999-2003 NASS peanut price was used.

Costs of Production: 2005 Texas Crop and Livestock Budgets produced by the Texas A&M Cooperative Extension Service for Districts 1&2 were the primary sources for costs of production. Costs are both crop and irrigation system specific. Electricity is the primary power source for this study area; therefore budgets were converted from natural gas to electricity when needed. The electricity price used was the South Plains Electric Coop 1998-2002 average price of .06442 $/kwh. Additionally, several sprinkler budgets were converted to furrow budgets when needed.

<u>Results</u>

Optimal levels of saturated thickness, annual net revenue per acre, pump lift, water applied per cropland acre, cost of pumping, and net present value of net returns per acre (NPV) by county were derived using the non-linear dynamic optimization model for the baseline scenario and the three water conservation policy alternatives for nineteen of the twenty-four counties in the study area. Five counties in the study area, Borden, Dickens, Howard, Martin, and Motley showed increases in saturated thickness over the sixty year planning horizon likely due to minimal irrigation in these counties. For this reason, policy results reported for these counties are for the baseline scenario, and the 0% drawdown policy; however, the remaining policy alternatives' results for these counties are not reported because the policy restrictions were non-binding and showed no deviation from the baseline.

Comparison of Policy Alternatives for Gaines County

In this section, comparisons pertaining to specific policy alternative results are relatively compared to the baseline.

0% Drawdown Policy to the Baseline: the constraint forcing all irrigated acres into dryland acres in the 0% drawdown policy caused significant differences in saturated thickness in year sixty compared to the baseline. Saturated thickness in the 0% case is 77 ft. above the baseline level. The model also showed major differences in the net revenue per acre. The 0% scenario nominal net revenue per acre was $96.00 less than the baseline in year two. The gap between nominal net revenue per acre did narrow slightly between the two scenarios in later time periods, but yearly baseline net revenue remained well above the 0% policy net revenue over the entire planning horizon. In the 0% drawdown scenario, NPV per acre was $2,278.81, or 81% lower than the baseline. Therefore, $2,278.81 would be the approximate per acre compensation that would have to be provided to Gaines County producers in year one for them to be no worse off by discontinuing water usage for sixty years.

50% Total Drawdown Policy to the Baseline: saturated thickness in the 50% drawdown scenario was 25.5 ft. above the baseline saturated thickness at the end of the planning horizon. Nominal net revenue per acre was interestingly not significantly affected by the 50% restriction remaining about $3.00 per acre below the baseline through year sixty. NPV per acre for the 50% policy was $531.34, or 19% below the baseline level.

75% Drawdown Policy to the Baseline: saturated thickness in the 75% drawdown scenario concluded 13 ft. above the baseline level whereas net revenue per acre remained similar to the baseline until year thirty-three. After year thirty-three, nominal net revenue per acre remained approximately $4.00 below the baseline level through year sixty. NPV per acre was determined to be only $222.08, or 8% below the baseline NPV.

50% Total Drawdown Policy to 50% Annual Drawdown Policy: as expected, saturated thickness in these two scenarios was quite similar with the saturated thickness in the 50% annual policy being 1.5 ft. higher than the 50% total policy in year sixty. In year two, the 50% total policy net revenue per acre was $48.00 higher than the 50% annual net revenue, however; by year twenty-three the 50% annual restriction had a higher net revenue per acre. At the end of the planning horizon, the 50% annual policy nominal net revenue per acre was $21.00 higher than the 50% total drawdown net revenue per acre. NPV per acre differs however: NPV for the 50% total drawdown policy is $388.95, or 20% higher than the 50% annual restriction implying that for about the same amount of water conservation, an annual water use restriction causes producers to be worse off than a sixty year planning horizon water use restriction.

Regional Results

As discussed previously, in the baseline scenario five counties in the region (Borden, Dickens, Howard, Martin, and Motley) showed an increase in the saturated thickness over the planning horizon in addition to comparatively low net revenue per acre and water applied per cropland acre. These counties lie relatively close to the eastern edge of the Ogallala Aquifer and currently have low saturated thickness levels and insignificant amounts of irrigation compared to other counties in the study area.

Apart from the five low saturated thickness counties mentioned above, results of the baseline scenario and policy alternatives showed generally consistent trends across the region in irrigation practices and cropping patterns.

Though the overall regional trends are similar in irrigation practices and cropping patterns, the results of the policies also show that the impacts of the policies differ greatly across the region. One major factor examined that demonstrates the major differences across the region is the cost of each policy. Table 1 on the following page depicts the implicit cost of water conservation per acre foot of saturated thickness on a cropland acre basis for the 0% drawdown Policy, the 50% total drawdown policy, and the 75% drawdown policy.

The cost of conserving an additional foot of saturated thickness in these policies is a direct effect of saturated thickness depletion and NPV for each scenario. Andrews, Howard, and Roosevelt Counties for example showed either no or a minute amount of aquifer depletion in the baseline; therefore, the cost of conserving an additional foot of saturated thickness is relatively high in those counties. The cost of an additional foot of saturated thickness conservation in Howard County is $2,281.00 for the reason that in the baseline scenario, the saturated thickness increases approximately the same level it does in the 0% policy: the year sixty saturated thickness is only 0.9 ft. higher than the baseline scenario in turn causing the significantly high cost. Alternatively, Hale and Lubbock Counties are high water use counties and showed significant levels of depletion in the baseline scenario. Therefore, the cost of an additional acre of foot in these counties is much lower.

Another interesting characteristic shown in Table 1 is the differences in the costs of conservation between policies. The cost of the 0% drawdown policy is notably higher than both the 50% total and the 75% policies for all counties in the study area. Conversely, the gap in the costs of an additional acre foot of conservation between the 50% total and the 75% policy are often in close proximity to one another. Gaines County for example shows that the cost of an additional acre foot of saturated thickness is only $3.77 more in the 50% policy than in the 75% policy.

Overall, the results of the study indicate that policy impacts vary greatly across the region. How a policy alternative will impact a county depends on the hydrologic characteristics of the county, the level of current irrigation, and the profitability of the optimal crops.

Policy Implications

0% Drawdown Policy: this policy conserved massive amounts of water in the Ogallala Aquifer; but it also significantly decreased NPV and likely agricultural economic activity across the region. This restrictive policy is not necessary for most counties in the region, and would likely have detrimental effects to the regional economy. The decrease in economic activity would be similar to the effects expected in the case of total aquifer exhaustion, which is what water conservation policies are attempting to circumvent. As stated previously, five counties showed an increase in saturated thickness throughout the planning horizon in the baseline scenario. Many other counties did exhibit aquifer drawdown in the baseline scenario,

Table 1: Implicit Cost in Dollars of Water Conservation Per Foot of Saturated Thickness By Policy On a Cropland Acre Basis

County	0%	50% Total	75%
Andrews	800.98	435.07	340.28
Bailey	21.38	10.12	7.11
Borden	341.89	N/A	N/A
Cochran	54.82	27.75	20.99
Crosby	25.43	11.90	8.24
Dawson	79.88	20.60	10.56
Dickens	70.03	N/A	N/A
Floyd	49.96	34.68	28.62
Gaines	29.56	20.81	17.04
Garza	119.78	55.00	37.11
Glasscock	43.41	8.91	4.29
Hale	38.60	33.81	29.56
Hockley	58.70	41.27	35.30
Howard	2281.00	N/A	N/A
Lamb	20.11	14.34	11.92
Lea	427.32	226.68	164.24
Lubbock	21.04	16.36	14.31
Lynn	82.68	29.43	14.30
Martin	473.23	N/A	N/A
Midland	112.42	47.32	27.87
Motley	80.17	N/A	N/A
Roosevelt	343.90	110.89	63.37
Terry	83.98	59.58	48.78
Yoakum	58.35	34.70	27.65

but not to the extent that a policy this restrictive on water use would be required across the region. This policy would be best used in only those counties, or areas of counties, with extensive annual aquifer drawdown, and be implemented on a portion of total cropland acres within a county.

<u>50% Total Drawdown Policy and 75% Drawdown Policy:</u> these two water conservation policies exhibited similar trends. Comparable to the 0% water conservation policy discussed above, neither of these two policies will likely be necessary across the study region. In many counties the 75% drawdown and often the 50% drawdown restrictions were not binding constraints because the levels of saturated thickness underlying those counties in the baseline scenario did not decline to the 50% or 75% drawdown levels.

Both the 50% total drawdown policy and the 75% drawdown policy caused a decrease from the baseline NPV and both conserved water in the aquifer relative to the baseline. The 75% policy had a slightly higher NPV than the 50% policy whereas the 50% drawdown policy conserved 25% more water than did the 75% policy.

These two policies were the most restricting on high water use counties. Hale County, the highest water use county in the study area, showed a NPV 16% lower than the baseline for the 50% policy while the 75% policy NPV was 7% lower than the baseline. However, the 50% policy conserved an additional 16 ft. more saturated thickness than did the 75% policy. Alternatively, Midland County is a low water use county. The NPV for the 50% total policy in this scenario was 7% less than the baseline whereas the 75% policy NPV was 2% below the baseline. However, in this case, the 50% policy conserved 4 ft. of saturated thickness relative to the baseline and the 75% policy conserved 3 ft. of saturated thickness relative to the baseline. Therefore, these water policy alternatives are likely not necessary for Midland County.

50% Annual Drawdown Policy: as with previously discussed scenarios, this Policy did not work well for low water use counties due to the fact that water use was so minute in the baseline scenario that restricting a county to half the baseline amount caused the discontinuation of irrigation practices. This policy alternative did conserve significant amounts of water in the high water use counties. Hale County for example, conserved 55 ft. of saturated thickness relative to the baseline while the NPV was 37% lower than the baseline. However, the cost of implementing this annual policy will likely be much greater than the cost of implement a similar sixty year policy.

Conclusions

The results from this study indicate that because of the significant differences in hydrologic characteristics and current irrigation levels across the study area, blanket water conservation policies for the region as a whole are likely to be inefficient. Under the baseline scenario, there are many counties in the study area that do not deplete saturated thickness to a level that warrants a conservation policy. As shown in the results section, the cost of conserving an additional acre foot of water in low water use counties is extremely high. Legislative time and tax money would be more efficiently spent enacting policies to conserve water in those counties that significantly utilize the aquifer underlying the county. After analyzing the water use practices and aquifer levels in each county, this study concludes that for this region, water conservation policies should focus on counties that deplete the aquifer to less than 30 ft. of saturated thickness in the baseline scenario; where the implicit cost of conserving a foot of saturated thickness is relatively low. These are the most heavily irrigated counties in the study region, and society as a whole would most likely benefit from the focus of water conservation being in these high water use counties.

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