COMPARISON OF WATER ALLOCATION STRATEGIES FOR WHEAT PRODUCTION IN THE TEXAS PANHANDLE

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Abstract: The declining availability of irrigation water from the Ogallala aquifer combined with increasing energy costs make irrigation strategies much more critical. Irrigation strategies that maximize returns to irrigation require less water and achieve higher returns than strategies aimed at satisfying 100% of the crops evapotranspiration (ET) requirements.

Key Words: irrigation efficiency, water response function, input use optimization, ET.

Irrigation has been the driving force in the development of the agricultural sector in the Texas Panhandle. The development and decline of irrigation in the region has occurred since the end of World War II in 1945. Between 1950 and 1980 irrigated acres increased from 19,315 to 1,754,560. Since 1980 irrigated acres have declined to 1,363,438. The water availability in the Ogalalla aquifer continues to decline and pumping costs continue to increase. This drastically reduces the profitability of agricultural production as irrigation increases yield by 2 to 7 times over non-irrigation and reduces variability in yield by 75% to 90%.

Since there is no renewable surface source of irrigation water in the Panhandle and only limited recharge of the Ogallala aquifer in this area, irrigation water is a fixed supply and excessive pumping results in shortening the economic life of the aquifer and reduces the returns to the resources held by the farmer (Amosson et al. 2001). Strategies that will maintain returns while conserving water are critical to the future of agriculture in the area.

The objectives of this study are: 1) to estimate the marginal value product of irrigation in the production of wheat, 2) evaluate alternative water management strategies, and 3) provide guidelines for determining water applications that will maximize return to irrigation and extend the productive life of the Ogallala Aquifer.

Data included in this study represents 114 observations of wheat production information collected from producers cooperating in the AgriPartners program, (New, 1998-2004). Participants in the AgriPartner program collected and recorded irrigation, rainfall, soil moisture, and other production information weekly. Final crop production data was provided after harvesting the wheat crop. Crop water requirements are determined by the Potential Evapotranspriation as reported by the North Plains PET Network (New, 1998-2004).

Two irrigation decision criteria: profit maximization, and 100% potential evapotranspriration are compared to determine optimum application levels for two management variables: irrigation to achieve the profit maximizing level of water availability, and irrigation to provide crop water requirements as indicated by percent potential evapotranspiration. Response functions are estimated for each of the water management variables to show the relationship between yield of wheat plus winter grazing and the management variable.

Evapotranspiration (ET) is an estimate of the water requirements of the crop. The Reference Evapotranspiration (ET_0) reflects biological factors such as: 1) the crop maturity rating, and 2) the stage of growth and climatic conditions such as: 1) maximum and minimum temperatures, growing degree days (GDD at 56 Degrees Fahrenheit), 2) humidity, 3) solar radiation, 4) wind speed and 5) direction. The three sources of water to meet ET requirements include: residual soil moisture, natural precipitation (rainfall), and irrigation (Almas, Colette, and Robinson, 2004).

Irrigation Costs

Total production cost is the sum of the fixed cost and the variable input cost incurred in the production process. In evaluating the optimum level of a single variable input, the levels of all of the inputs except irrigation are assumed constant and are included in fixed cost. Only the cost irrigation is included in variable cost. Since all irrigation in the region uses groundwater, the variable cost associated with irrigation represents pumping and application costs including: fuel cost; cost of lubrication, maintenance, and repairs; labor costs; and annual investment costs (Equation 1) (Almas et al. 2000).

(1) $$TC = FC + NIPC + (FULC + LMR + LC + AIC)W$$

Where:

TC is the total production cost,

FC + NIPC is the cost associated with the fixed inputs,
NIPC are the costs associated with production inputs other than irrigation,
FULC is the fuel cost per acre inch of water,
LMR is the cost of lubrication, maintenance and repairs,
LC is labor cost per acre inch of water,
AIC is annual investment cost per acre inch of water, and
W is the amount of water available to meet ET requirements.

The impact of a change in the price of fuel is observed in the change in the cost of fuel. Since natural gas is the predominate source of energy for irrigation in the area, natural gas is used in the calculations. The fuel cost (FULC) is equal to the product of the amount of fuel used (NG) multiplied by the price of the fuel (P_{NG}) (Equation 2).

(2) $$FULC = NG*P_{NG}$$

In turn the amount of natural gas needed to pump and deliver one inch of water depends on the efficiency of the system, the lift required to get the water from below the ground to the delivery system, and the pressure of the delivery system (Equation 3).

(3) $$NG = 0.0038*L + 0.088*PSI - ((7.623E\text{-}6)*PSI)*(L) - (3.3E\text{-}6)*L^2$$

Where:
NG is the mcf of natural gas
L is the system lift in feet
PSI is the system pressure per square inch

The NG, LMR, LC and AIC are known constants for a given irrigation system. (Almas 2000). For example, the Total Cost function for a typical Low Elevation Spray Application (LESA) system with a 350 foot system lift can be expressed as Equation 4.

(4) $$TC = FC + NIPC + (1.018P_{NG} + 2.50 + 0.91 + 3.81)W$$

The Marginal Factor Cost of water (MFC_W) is the first partial derivative of the cost function with respect to the input, water (W) (Equation 5).

(5) $$MFC_W = \frac{\partial TC}{\partial W}$$

$$MFC_W = 1.018 P_{NG} + 2.50 + 0.91 + 3.81$$

$$MFC_W = 1.018 P_{NG} + 7.22$$

Returns from Complementary Grazing: Grazing winter wheat during the November to March period in the Texas Panhandle is a complementary activity as it contributes additional income without reducing the yield of grain as long as the livestock are removed before the emergence of the seed stocks. Therefore, optimization can be calculated for grain production and then the complementary income from grazing added to the return.

The relationship between grazing and water availability, whether provided by irrigation or natural precipitation, is estimated by fitting a quadratic function to data obtained from the District 1 Crop Budgets prepared by the Texas Cooperative Extension Service.

(6) Grazing Units = -224.1940 + 27.6693*AW – 0.3065*AW2

Where: Grazing Units are one-third of a day for a 450 lb. steer,
AW is inches of available water.

Estimation of response function, marginal value product, and economic optimum level of available water for wheat: A quadratic response function is estimated to relate the production of wheat grain to the water available from natural precipitation, soil moisture, and supplemental irrigation, Table 1,

The Marginal Physical Product of Water in wheat grain (MPP_{WW}) is equal to the partial derivative of the response function with respect to the input available water. The Marginal Value Product of available water in wheat grain production (MVP_{WW}) is obtained by multiplying the Marginal Physical Product of water in wheat grain production (MPP_{WW}) by the price of wheat (P_W) (Equation 7).

(7)
$$MVP_{WW} = MPP_{WW} * P_W$$
$$MVP_{WW} = (5.3035 - 0.1788AW)P_W$$

Where:

MVP_{WW} is the Marginal Value Product of Available Water in the production of wheat grain,
AW is the availability of Water from precipitation, soil water, and irrigation, and
P_W is the Price of Water.

The optimum level of Available Water is determined by equating the Marginal Value Product of Available Water with the Marginal Factor Cost of Water, Equation 8.

(8)
$$MVP_{WW} = MFC_W$$
$$(5.3035 - 0.1788AW)P_W = 1.018P_{NG} + 7.22$$

Solving equation 7 for AW gives a function in the Price of Wheat (PW) and the Price of Natural Gas (PNG), Equation 9.

(9)
$$AW = \frac{5.3035 - \frac{1.018P_{NG} + 7.22}{P_W}}{0.1788}$$

Optimum levels of Available Water for Prices of Wheat from \$3 to \$6.50 and Natural Gas prices from \$4 to \$12.50 are shown in Table 2.

The optimal levels of water availability that will maximize the net returns increase as the Price of Wheat (P_W) increases and decreases as the Price of Natural Gas (P_{NG}) increases. Plug the optimal water level from Table 1 into the response function to determine the expected yield associated that level of variable input use. The yield that maximizes the returns to available water ranges from 28.89 bushels per acre (bpa) to 78.11 (bpa) depending on the combination if input and output prices. The optimal yield increases as the Price of Wheat increases and decreases as the Price of Natural Gas increases.

Amarillo Precipitation

Wheat production in the 26 counties in the Texas Panhandle is dependent on the amount of precipitation received during the growing season from September through May. Monthly precipitation records recorded at the Amarillo Airport are used to construct the distribution of September through May precipitaion. The mean September through May seasonal precipitation at Amarillo is 14.06 inches. The standard deviation of September through May precipitation is 4.78 inches. The first and fourth quartile have been calculated to represent bove and below average precipitation. The first quartile value is 17.29 inches and the fourth quartile value is 10.85 inches.

Returns to Irrigation

Since the available water response function includes natural precipitation in addition to the management irrigation, the irrigaion requirement is obtained by subtracting the precipitation from the optimal available water level. The expected irrigation level under average precipitation is obtained by subtracting average September through June precipitation, 14.06 inches, from the optimal level of available water.

The return to irrigation is calculated as the difference between the net return with irrigation and that without irrigation, Table 3. The return with irrigation is calculated by multiplying the yield obtained with optimal available water by the price of wheat, adding the return from grazing, and subtracting the production cost. The return without irrigation is based on the yield obtained with average precipitation of 14.06 inches. Under average precipitation conditions the returns to irrigation are negative for Prices of Wheat below $5 for all levels of Price of Natural Gas included in the study. Returns to irrigation increase as the Price of Wheat increases, reaching a return of $25.54 with a wheat price of $6.50 and natural gas price of $4. At higher wheat prices increases in natural gas prices reduce the return to irrigation. At lower wheat prices increases in natural gas prices result in reducing the negative returns as the level of irrigation decreases relatively faster than the increase in price resulting in a reduction in the loss.

The expected irrigation level corresponding to the first quartile of precipitation is obtained by subtracting September through June precipitation of 17.29 inches from the optimal level of available water. The irrigation requirements are less given first quartile precipitation than under average precipitation. The desired irrigation level increases as the Price of Wheat increases and decreases as the Price of Natural Gas increases. At combinations of high input price and low output price irrigation is not indicated, Table 4.

Under above average, first quartile, precipitation conditions the returns to irrigation are negative for all combinations of input and output prices except a Prices of Wheat of $6.50 and a Price of Natural Gas of $4. With this one exception economic returns to irrigation are negative when September through June precipitation is in the top 25% of the distribution. At higher wheat prices increases in natural gas prices reduce the return to irrigation. At lower wheat prices increases in natural gas prices result in reducing the negative returns as the level of irrigation decreases relatively faster than the increase in price resulting in a reduction in the loss.

The expected irrigation level corresponding to the fourth quartile of precipitation is obtained by subtracting September through June precipitation of 10.85 inches from the optimal level of available water. The irrigation requirements are greater given fourth quartile precipitation than under average precipitation. Irrigation levels vary up to 15.30 acre inches. The desired irrigation level increases as the Price of Wheat increases and decreases as the Price of Natural Gas increases. At combinations of high input price and low output price optimal available water levels are less than expected precipitation, therefor, irrigation is not indicated.

Under below average, fourth quartile, precipitation conditions of 10.85 inches the economic returns to irrigation greater than under either average or above average precipitation. Return to irrigation increases as the Price of Wheat increases and decreases as energy price increases. When the Price of Natural Gas is $4 the return to irrigation becomes positive at a Price of Wheat of $4 and increases to $63.08 per acre at a Price of Wheat of $6.50. At higher wheat prices increases in natural gas prices reduce the return to irrigation. At lower wheat prices increases in natural gas prices result in reducing the negative returns as the level of irrigation decreases relatively faster than the increase in price resulting in a reduction in the loss.

Estimation of a response function utilizing PPET to determine marginal value product, and economic optimum level of irrigation for wheat production

A linear response function is estimated to relate wheat production to Percent Potential Evapotransiration. Potential evapotranspiration (PET) is reported daily during the growing season to participants in the North Plains Evapotranspiration Network. The information is used to schedule irrigations so as to meet the water requirements of the growing crop, Table 6.

Percent Potential Evapotranspiration is a decision variable but is not a management variable in that it can be recorded but it cannot be physically controlled, purchased or applied. The management variable associated with PPET is the amount of water made available to produce the crop in order to achieve the desired percentage of the total water requirements of the growing crop. This value is estimated by the regression model of PPET as a function of Available Water. The Analysis of Variance for this model is shown in Table 7.

By application of the chain rule it is possible to determine the optimal level of PPET. The Marginal Physical Product of wheat with respect to the management variable, Available Water, is determined by multiplying the partial derivative of Yield with respect to PPET by the partial derivative of PPET with respect to Available Water. The Marginal Value Product of Available Water can then be determined by multiplying the Marginal Physical Product by the Price per bushel for wheat.

The optimal level of Available Water to satisfy PPET requirements is determined by equating the Marginal Value Product of Available Water to the Marginal Factor Cost of an additional acre inch of water and solving for the level of Available Water, Equation 10.

$$MVP_W = \left(\frac{\partial TTP}{\partial PPET} * \frac{\partial PPET}{\partial W}\right) * P_W$$

$$MVP_W = (0.5418 * (8.0677 - 0.2698 AW)) * P_W$$

$$MVP_W = (4.3711 - 0.1462 AW) * P_W$$

(10)

$$MVP_W = MFC_W$$

$$(4.3711 - 0.1462 AW) * P_W = 1.018 * P_{NG} + 7.22$$

$$AW = \frac{4.3711 - \frac{1.018 * P_{NG} + 7.22}{P_W}}{0.1462}$$

The optimal level of Available Water to satisfy PPET requirements for combinations of the Price of Wheat from \$3 to \$6.50 and the Price of Natural Gas from \$4 to \$12.50 are shown in Table 8. The optimal levels of water availability that will maximize the net returns to irrigation increase as the Price of Wheat (P_W) increases and decreases as the Price of Natural Gas (P_{NG}) increases. At combinations of low wheat prices and high natural gas prices it is not profitable to apply any irrigation water for the wheat crop. The maximum beneficial water availability under the price combinations included in the table is 25.61 acre inches. The optimal PPET for wheat production is obtained by inserting optimal amount of Available Water from Table 8 into the

PPET as a function of Available Water equation and solving for the PPET, Table 9.

The expected irrigation level under average precipitation is obtained by subtracting average September through June precipitation, 14.06 inches, from the optimal level of available water in Table 9.

Irrigation levels range up to 11.55 acre inches. The required irrigation level increases as the Price of Wheat increases and decreases as the Price of Natural Gas increases. At combinations of high input price and low output price irrigation is not indicated.

Under average precipitation conditions, 14.06 inches, the returns to irrigation are negative for Prices of Wheat below $6 for all levels of Price of Natural Gas above $5, Table 10.

The expected irrigation level corresponding to the first quartile of precipitation is obtained by subtracting September through June precipitation of 17.29 inches from the optimal level of available water. The irrigation requirements are less given first quartile precipitation than under average precipitation. The desired irrigation level increases as the Price of Wheat increases and decreases as the Price of Natural Gas increases. At combinations of high input price and low output price irrigation is not indicated.

Under above average, first quartile, precipitation conditions of 17.29 inches the returns to irrigation are negative for all combinations of input ant output prices. Economic returns to irrigation are negative when September through June precipitation is in the top 25% of the distribution, Table 11.

The expected irrigation level corresponding to the fourth quartile of precipitation is obtained by subtracting September through June precipitation of 10.85 inches from the optimal level of available water to satisfy PPET. The irrigation requirements are greater given fourth quartile precipitation than under average precipitation. Irrigation levels vary up to 14.76 acre inches. The desired irrigation level increases as the Price of Wheat increases and decreases as the Price of Natural Gas increases. At combinations of high input price and low output price optimal available water levels are less than expected precipitation, therefor, irrigation is not indicated.

Under below average, fourth quartile, precipitation conditions of 10.85 inches the economic returns to irrigation greater than under either average or above average precipitation, Table 12. Returns to irrigation increase as the Price of Wheat increases and decrease as the Price of Natural Gas increases. When the Price of Natural Gas is $4 the return to irrigation becomes positive at a Price of Wheat of $5 and increases to $33.45 per acre at a Price of Wheat of $6.50. At higher wheat prices increases in natural gas prices reduce the return to irrigation. At lower wheat prices increases in natural gas prices result in reducing the negative returns as the level of irrigation decreases relatively faster than the increase in price resulting in a reduction in the loss.

Discussion

Irrigation has been very beneficial to the development of agriculture in the Texas Panhandle. It has increased yields and revenues, and has decreased risk. However, as the depletion of the Ogalalla Aquifer and the increase in energy prices has increased production costs while commodity prices have either remained steady or decreased, irrigation and irrigation levels have become of much more critical importance to the economic benefit of producers.

Two management decision criteria are evaluated in this study; 1) utilizing measurement of available water from natural precipitation, soil water, and irrigation to determine the optimal amount of irrigation to maximize the returns to irrigation, and 2) using the Percent Potential Evapotranspiration (PPET) to determine the optimal amount of irrigation to apply to maximize the returns to irrigation. The two management decision variables are evaluated under average, first quartile, and fourth quartile levels of natural September through June precipitation measured at the Amarillo International Airport. Both management decision variables produce the same pattern of irrigation and return. Both indicate that under average September through June precipitation returns to irrigation are positive for only combinations of high crop prices and low energy costs. Both decision variables indicate that returns to irrigation are negative when natural precipitation is in the first quartile. This indicates that with above average natural precipitation irrigation may increase yields, but the increased revenue will be more than offset by the increase in cost and the net result is a reduction in net profit. Both criteria indicate that when September through June natural precipitation is in the fourth quartile that returns to irrigation are greatly increased. Under below normal natural precipitation conditions irrigation becomes more profitable. Supplemental irrigation for wheat when precipitation is low increases yield, revenue and net profit while reducing risk. The criterion based on available water appears to give a better range of results and indicates higher irrigation levels and higher returns to irrigation than the method utilizing PPET.

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Table 1. ANOVA for the Model Grain Yield of Wheat as a Function of Available Water for the Texas Panhandle, 1998-2004.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	17,467.68	8,733.84	19.04	<.0001
Error	111	50,924.85	458.78		
Total, Corrected	113	68,392.53			

R-Square	Coeff Var	Root MSE	Yield Mean
0.2554	34.1987	21.4192	62.6316

Source	DF	Type I SS	Mean Square	F	Pr > F
AW	1	15,510.02	15,510.02	33.81	<.0001
AW^2	1	1,957.66	1,957.66	4.27	0.0412

Source	DF	Type III SS	Mean Square	F	Pr > F
AW	1	4,892.51	4,892.51	10.66	0.0015
AW^2	1	1,957.66	1,957.66	4.27	0.0412

Parameter	Parameter Estimate	Standard Error	t Value	Pr > t
Intercept	0.5492	14.5277	0.04	0.9699
AW	5.3035	1.6241	3.27	0.0015
AW^2	-0.0894	0.0433	-2.07	0.0412

Table 2. Optimal Levels of Available Water in Acre Inches for Wheat Production in the 26 Counties of the Texas Panhandle for Various Levels of the Price of Wheat and Price of Natural Gas, 1998-2004.

	P_W (\$)							
P_{NG} (\$)	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
4.00	22.07	23.15	23.97	24.60	25.11	25.52	25.87	26.16
4.50	21.12	22.34	23.26	23.97	24.54	25.00	25.39	25.72
5.00	20.17	21.53	22.54	23.34	23.97	24.49	24.92	25.28
5.50	19.22	20.71	21.83	22.70	23.40	23.97	24.44	24.84
6.00	18.27	19.90	21.12	22.07	22.83	23.45	23.97	24.41
6.50	17.33	19.09	20.41	21.44	22.26	22.93	23.49	23.97
7.00	16.38	18.27	19.70	20.81	21.69	22.42	23.02	23.53
7.50	15.43	17.46	18.99	20.17	21.12	21.90	22.54	23.09
8.00	14.48	16.65	18.27	19.54	20.55	21.38	22.07	22.65
8.50	13.53	15.83	17.56	18.91	19.98	20.86	21.60	22.22
9.00	12.58	15.02	16.85	18.27	19.41	20.34	21.12	21.78
9.50	11.63	14.21	16.14	17.64	18.84	19.83	20.65	21.34
10.00	10.68	13.39	15.43	17.01	18.27	19.31	20.17	20.90
10.50	9.73	12.58	14.72	16.38	17.71	18.79	19.70	20.46
11.00	8.79	11.77	14.00	15.74	17.14	18.27	19.22	20.03
11.50	7.84	10.95	13.29	15.11	16.57	17.76	18.75	19.59
12.00	6.89	10.14	12.58	14.48	16.00	17.24	18.27	19.15
12.50	5.94	9.33	11.87	13.85	15.43	16.72	17.80	18.71

Table 3. Return to Irrigation for Wheat Production in the 26 Counties of the Texas Panhandle or Various Levels of the Price of Wheat and Price of Natural Gas Based on Average September through June Precipitation (14.06 in.) and the Available Water Respons

	P_W ($)							
P_{NG} ($)	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
4.00	-20.69	-17.60	-12.63	-6.40	0.74	8.55	16.85	25.54
4.50	-19.73	-17.82	-13.77	-8.24	-1.69	5.64	13.54	21.88
5.00	-18.36	-17.69	-14.58	-9.81	-3.86	2.96	10.44	18.43
5.50	-16.60	-17.21	-15.08	-11.09	-5.77	0.53	7.57	15.19
6.00	-14.44	-16.38	-15.27	-12.08	-7.42	-1.66	4.92	12.14
6.50	-11.88	-15.19	-15.14	-12.79	-8.81	-3.62	2.49	9.31
7.00	-8.91	-13.65	-14.69	-13.21	-9.94	-5.33	0.28	6.68
7.50	-5.55	-11.75	-13.93	-13.35	-10.81	-6.81	-1.71	4.25
8.00	-1.79	-9.50	-12.85	-13.21	-11.42	-8.05	-3.48	2.03
8.50	NI	-6.90	-11.46	-12.77	-11.77	-9.05	-5.03	0.02
9.00	NI	-3.95	-9.75	-12.06	-11.86	-9.81	-6.35	-1.79
9.50	NI	-0.64	-7.72	-11.05	-11.69	-10.33	-7.46	-3.40
10.00	NI	NI	-5.38	-9.77	-11.26	-10.62	-8.34	-4.80
10.50	NI	NI	-2.73	-8.19	-10.57	-10.66	-9.01	-5.99
11.00	NI	NI	NI	-6.34	-9.62	-10.47	-9.45	-6.98
11.50	NI	NI	NI	-4.19	-8.42	-10.04	-9.67	-7.76
12.00	NI	NI	NI	-1.77	-6.95	-9.36	-9.68	-8.34
12.50	NI	NI	NI	NI	-5.22	-8.45	-9.46	-8.71

Table 4. Return to Irrigation for Wheat Production in the 26 Counties of the Texas Panhandle for Various Levels of the Price of Wheat and Price of Natural Gas Based on Above Average Precipitation and the Available Water Response Function, 1998-2004.

	P_W ($)							
P_{NG} ($)	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
4.00	-17.20	-18.15	-17.22	-15.02	-11.91	-8.14	-3.88	0.78
4.50	-14.60	-16.73	-16.71	-15.22	-12.70	-9.41	-5.55	-1.23
5.00	-11.60	-14.96	-15.88	-15.15	-13.23	-10.44	-7.00	-3.04
5.50	-8.19	-12.84	-14.74	-14.78	-13.50	-11.23	-8.23	-4.65
6.00	-4.39	-10.36	-13.29	-14.13	-13.51	-11.78	-9.24	-6.05
6.50	-0.18	-7.53	-11.51	-13.20	-13.25	-12.10	-10.03	-7.24
7.00	NI	-4.34	-9.42	-11.98	-12.74	-12.17	-10.59	-8.23
7.50	NI	-0.81	-7.02	-10.48	-11.97	-12.01	-10.94	-9.01
8.00	NI	NI	-4.30	-8.69	-10.94	-11.60	-11.07	-9.59
8.50	NI	NI	-1.26	-6.62	-9.65	-10.96	-10.97	-9.96
9.00	NI	NI	NI	-4.26	-8.10	-10.08	-10.66	-10.13
9.50	NI	NI	NI	-1.61	-6.28	-8.96	-10.12	-10.09
10.00	NI	NI	NI	NI	-4.21	-7.60	-9.36	-9.85
10.50	NI	NI	NI	NI	-1.88	-6.01	-8.38	-9.40
11.00	NI	NI	NI	NI	NI	-4.17	-7.19	-8.75
11.50	NI	NI	NI	NI	NI	-2.09	-5.77	-7.89
12.00	NI	NI	NI	NI	NI	NI	-4.13	-6.83
12.50	NI	NI	NI	NI	NI	NI	-2.26	-5.56

Table 5. Return to Irrigation for Wheat Production in the 26 Counties of the Texas Panhandle for Various Levels of the Price of Wheat and Price of Natural Gas Based on Below Average Precipitation (10.85 in.) and the Available Water Response Function, 1998

	P_W ($)							
P_{NG} ($)	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
4.00	-17.67	-9.65	0.25	11.42	23.49	36.23	49.46	63.08
4.50	-18.34	-11.50	-2.51	7.94	19.43	31.68	44.52	57.80
5.00	-18.61	-13.01	-4.96	4.74	15.63	27.38	39.79	52.71
5.50	-18.48	-14.16	-7.10	1.83	12.08	23.31	35.29	47.83
6.00	-17.95	-14.95	-8.91	-0.80	8.80	19.49	31.00	43.16
6.50	-17.02	-15.40	-10.41	-3.14	5.78	15.90	26.94	38.69
7.00	-15.69	-15.49	-11.60	-5.19	3.02	12.55	23.10	34.43
7.50	-13.96	-15.22	-12.47	-6.96	0.51	9.44	19.48	30.37
8.00	-11.83	-14.61	-13.03	-8.45	-1.73	6.57	16.08	26.52
8.50	-9.30	-13.64	-13.26	-9.65	-3.71	3.94	12.90	22.87
9.00	-6.36	-12.32	-13.19	-10.56	-5.44	1.55	9.94	19.43
9.50	-3.03	-10.64	-12.79	-11.19	-6.90	-0.61	7.20	16.19
10.00	NI	-8.61	-12.09	-11.54	-8.10	-2.52	4.68	13.16
10.50	NI	-6.23	-11.06	-11.60	-9.04	-4.20	2.39	10.33
11.00	NI	-3.50	-9.72	-11.37	-9.73	-5.64	0.31	7.71
11.50	NI	-0.41	-8.07	-10.86	-10.15	-6.84	-1.54	5.30
12.00	NI	NI	-6.10	-10.06	-10.31	-7.80	-3.18	3.09
12.50	NI	NI	-3.81	-8.98	-10.22	-8.52	-4.59	1.08

Table 6. ANOVA for the Model Wheat Yield of as a Function of Percent Potential Evapotranspiration (PPET) for the 26 Counties in the Texas Panhandle, 1998-2004.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	17,043.26	17,043.26	37.17	<.0001
Error	112	51,349.26	458.48		
Total, Corr	113	68,392.53			

R-Square	Coeff Var	Root MSE	Yield Mean
0.2492	34.1873	21.4120	62.63

Source	DF	Type I SS	Mean Square	F	Pr > F
PPET	1	17,043.26	17,043.26	37.17	<.0001

Source	DF	Type III SS	Mean Square	F	Pr > F
PPET	1	17,043.26	17,043.26	37.17	<.0001

Parameter	Parameter Estimate	Standard Error	t Value	Pr > t
Intercept	20.7468	7.1564	2.9000	0.0045
PPET	0.5418	0.0889	6.1000	<.0001

Table 7. ANOVA for the Model Potential Evapotranspiration (PPET) for Wheat as a Function of Available Waterfor the 26 Counties in the Texas Panhandle, 1998-2004.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	41,272.00	20,636.00	136.44	<.0001
Error	111	16,788.25	151.25		
Total, Corr	113	58,060.25			

R-Square	Coeff Var	Root MSE	Yield Mean
0.7108	15.9083	12.2982	77.31

Source	DF	Type I SS	Mean Square	F	Pr > F
AW	1	36,813.19	36,813.19	243.40	<.0001
AW^2	1	4,458.82	4,458.82	29.48	<.0001

Source	DF	Type III SS	Mean Square	F	Pr > F
AW	1	11,321.46	11,321.46	74.85	<.0001
AW^2	1	4,458.82	4,458.82	29.48	<.0001

Parameter	Parameter Estimate	Standard Error	t Value	Pr > t
Intercept	-17.4901	8.3413	-2.10	0.0383
AW	8.0677	0.9325	8.65	<.0001
AW^2	-0.1349	0.0248	-5.43	<.0001

Table 8. Optimal Levels of Available Water to Satisft PPET Requirements for Wheat Production for the 26 Counties of the Texas Panhandle for Various Levels of the Price of Wheat and Price of Natural Gas, 1998-2004.

	P_W ($)							
P_{NG} ($)	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
4.00	20.61	21.94	22.94	23.71	24.33	24.83	25.26	25.61
4.50	19.45	20.95	22.06	22.94	23.63	24.20	24.68	25.08
5.00	18.29	19.95	21.19	22.16	22.94	23.57	24.10	24.54
5.50	17.13	18.96	20.32	21.39	22.24	22.94	23.52	24.01
6.00	15.97	17.96	19.45	20.61	21.54	22.30	22.94	23.47
6.50	14.81	16.97	18.58	19.84	20.85	21.67	22.35	22.94
7.00	13.65	15.97	17.71	19.07	20.15	21.04	21.77	22.40
7.50	12.49	14.98	16.84	18.29	19.45	20.40	21.19	21.86
8.00	11.33	13.98	15.97	17.52	18.76	19.77	20.61	21.33
8.50	10.17	12.99	15.10	16.75	18.06	19.14	20.03	20.79
9.00	9.01	11.99	14.23	15.97	17.36	18.50	19.45	20.26
9.50	7.85	11.00	13.36	15.20	16.67	17.87	18.87	19.72
10.00	6.69	10.00	12.49	14.42	15.97	17.24	18.29	19.19
10.50	5.53	9.01	11.62	13.65	15.28	16.60	17.71	18.65
11.00	4.37	8.01	10.75	12.88	14.58	15.97	17.13	18.11
11.50	3.21	7.02	9.88	12.10	13.88	15.34	16.55	17.58
12.00	2.05	6.02	9.01	11.33	13.19	14.71	15.97	17.04
12.50	0.89	5.03	8.14	10.56	12.49	14.07	15.39	16.51

Table 9. Percent Potential Evapotranspiration (PPET) that Optimizes the Return to Irrigation for Wheat Production for Various Prices for Wheat and Natural Gas for the 26 Counties in the Texas Panhandle, 1998-2004.

	P_W ($)							
P_{NG} ($)	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
4.00	91.49	94.58	96.58	97.96	98.94	99.67	100.22	100.65
4.50	88.40	92.31	94.84	96.58	97.83	98.75	99.45	99.99
5.00	84.95	89.77	92.90	95.05	96.58	97.72	98.58	99.26
5.50	81.13	86.97	90.76	93.35	95.21	96.58	97.63	98.44
6.00	76.95	83.90	88.40	91.49	93.70	95.34	96.58	97.55
6.50	72.41	80.56	85.85	89.47	92.07	93.99	95.45	96.58
7.00	67.50	76.95	83.09	87.29	90.30	92.53	94.22	95.54
7.50	62.23	73.08	80.12	84.95	88.40	90.96	92.90	94.41
8.00	56.60	68.94	76.95	82.45	86.38	89.28	91.49	93.21
8.50	50.60	64.54	73.58	79.78	84.22	87.50	89.99	91.94
9.00	44.24	59.86	70.00	76.95	81.93	85.61	88.40	90.58
9.50	37.52	54.92	66.22	73.96	79.51	83.60	86.72	89.15
10.00	30.43	49.72	62.23	70.81	76.95	81.50	84.95	87.64
10.50	22.98	44.24	58.04	67.50	74.27	79.28	83.09	86.05
11.00	15.17	38.50	53.65	64.03	71.46	76.95	81.13	84.39
11.50	6.99	32.49	49.05	60.40	68.51	74.52	79.09	82.64
12.00	-1.55	26.22	44.24	56.60	65.44	71.98	76.95	80.82
12.50	-10.45	19.68	39.23	52.64	62.23	69.33	74.73	78.93

Table 10. Returns to Irrigation for Wheat Production for the 26 Counties of the Texas Panhandle for Various Levels of the Price of Wheat and Price of Natural Gas Based on Average September through June Precipitation (14.06 in.) and Optimal PPET.

	P_W ($)							
P_{NG} ($)	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
4.00	-21.15	-21.35	-19.31	-15.75	-11.11	-5.67	0.37	6.88
4.50	-18.49	-20.09	-19.13	-16.43	-12.48	-7.62	-2.07	4.03
5.00	-15.36	-18.42	-18.58	-16.77	-13.55	-9.29	-4.24	1.42
5.50	-11.77	-16.33	-17.66	-16.77	-14.31	-10.67	-6.15	-0.93
6.00	-7.71	-13.83	-16.36	-16.44	-14.75	-11.77	-7.79	-3.05
6.50	-3.18	-10.91	-14.69	-15.76	-14.89	-12.58	-9.17	-4.91
7.00	NI	-7.57	-12.65	-14.75	-14.72	-13.11	-10.29	-6.53
7.50	NI	-3.82	-10.23	-13.40	-14.23	-13.35	-11.14	-7.91
8.00	NI	NI	-7.44	-11.71	-13.44	-13.30	-11.73	-9.04
8.50	NI	NI	-4.28	-9.68	-12.34	-12.97	-12.05	-9.92
9.00	NI	NI	-0.74	-7.31	-10.93	-12.36	-12.11	-10.55
9.50	NI	NI	NI	-4.60	-9.21	-11.45	-11.90	-10.94
10.00	NI	NI	NI	-1.55	-7.17	-10.27	-11.43	-11.09
10.50	NI	NI	NI	NI	-4.83	-8.80	-10.70	-10.98
11.00	NI	NI	NI	NI	-2.18	-7.04	-9.70	-10.63
11.50	NI	NI	NI	NI	NI	-5.00	-8.43	-10.04
12.00	NI	NI	NI	NI	NI	-2.67	-6.91	-9.20
12.50	NI	NI	NI	NI	NI	-0.06	-5.11	-8.11

Table 11. Returns to Irrigation for Wheat Production for the 26 Counties of the Texas Panhandle or Various Levels of the Price of Wheat and Price of Natural Gas Based on Above Average September through June Precipitation (17.29 in.) Based on Optimal PPET.

	P_W ($)							
P_{NG} ($)	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
4.00	-13.58	-17.14	-18.46	-18.25	-16.97	-14.88	-12.20	-9.04
4.50	-9.28	-14.24	-16.64	-17.29	-16.70	-15.19	-12.99	-10.25
5.00	-4.51	-10.92	-14.44	-15.99	-16.12	-15.22	-13.52	-11.21
5.50	NI	-7.19	-11.88	-14.35	-15.24	-14.96	-13.79	-11.93
6.00	NI	-3.05	-8.94	-12.37	-14.04	-14.41	-13.79	-12.40
6.50	NI	NI	-5.63	-10.05	-12.54	-13.58	-13.53	-12.63
7.00	NI	NI	-1.94	-7.40	-10.72	-12.46	-13.00	-12.60
7.50	NI	NI	NI	-4.40	-8.60	-11.06	-12.21	-12.34
8.00	NI	NI	NI	-1.07	-6.16	-9.38	-11.16	-11.82
8.50	NI	NI	NI	NI	-3.42	-7.40	-9.84	-11.06
9.00	NI	NI	NI	NI	-0.36	-5.14	-8.25	-10.05
9.50	NI	NI	NI	NI	NI	-2.60	-6.40	-8.80
10.00	NI	NI	NI	NI	NI	NI	-4.29	-7.30
10.50	NI	NI	NI	NI	NI	NI	-1.91	-5.56
11.00	NI	NI	NI	NI	NI	NI	NI	-3.56
11.50	NI	NI	NI	NI	NI	NI	NI	-1.33
12.00	NI	NI	NI	NI	NI	NI	NI	NI
12.50	NI	NI	NI	NI	NI	NI	NI	NI

Table 12. Returns to Irrigation for Wheat Production for the 26 Counties of the Texas Panhandle for Various Levels of the Price of Wheat and Price of Natural Gas Based on Below Average September through June Precipitation (10.85 in.) and the Optimal PPET.

	P_W ($)							
P_{NG} ($)	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50
4.00	-23.19	-19.30	-13.18	-5.53	3.20	12.73	22.86	33.45
4.50	-22.16	-19.68	-14.63	-7.84	0.19	9.14	18.79	28.97
5.00	-20.67	-19.64	-15.71	-9.81	-2.51	5.84	14.98	24.73
5.50	-18.71	-19.18	-16.42	-11.45	-4.89	2.83	11.44	20.74
6.00	-16.28	-18.31	-16.76	-12.75	-6.97	0.10	8.16	17.00
6.50	-13.38	-17.02	-16.72	-13.70	-8.74	-2.34	5.15	13.50
7.00	-10.02	-15.32	-16.31	-14.32	-10.20	-4.50	2.40	10.25
7.50	-6.19	-13.21	-15.52	-14.60	-11.35	-6.37	-0.08	7.24
8.00	-1.90	-10.67	-14.36	-14.54	-12.19	-7.96	-2.30	4.48
8.50	NI	-7.73	-12.83	-14.14	-12.72	-9.26	-4.25	1.97
9.00	NI	-4.36	-10.93	-13.41	-12.94	-10.28	-5.94	-0.30
9.50	NI	-0.58	-8.65	-12.33	-12.85	-11.01	-7.37	-2.32
10.00	NI	NI	-6.00	-10.92	-12.45	-11.46	-8.53	-4.10
10.50	NI	NI	-2.97	-9.16	-11.74	-11.62	-9.43	-5.63
11.00	NI	NI	NI	-7.07	-10.72	-11.49	-10.06	-6.91
11.50	NI	NI	NI	-4.64	-9.39	-11.08	-10.43	-7.95
12.00	NI	NI	NI	-1.87	-7.75	-10.39	-10.53	-8.74
12.50	NI	NI	NI	NI	-5.80	-9.41	-10.37	-9.28