MODEL TO EVALUATE ALTERNATIVE IRRIGATION DISTRIBUTION SYSTEMS WITH AN EXHAUSTIBLE WATER SUPPLY*

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In many regions, irrigation water is pumped from an underground aquifer that receives little or no recharge. With an exhaustible water supply, water available in year t + 1 depends on quantity of water available in year t − 1 and the quantity withdrawn in year t. As the water supply decreases, pumping costs increase and returns to water and management decline.

The exhaustible nature of the water supply causes an especially difficult problem for the farm operator in that he must allocate water within and among years. In addition, the farm operator is faced with irrigation investment decisions; e.g., type of irrigation distribution system to use. He must consider simultaneously, labor intensive versus capital intensive systems and effect of each system on present value and economic life of his specific water supply. To manually evaluate the alternatives, making the necessary calculations would be prohibitive in terms of both cost and time.

The purpose of this study was to develop a general model whereby alternative irrigation distribution systems could be evaluated as to their effect on present value and economic life of any specified quantity of water. The developed model was then applied to the Southern High Plains of Texas [8].

The study is similar to previous studies of this area in that it is concerned with present value and economic life of an exhaustible irrigation water supply [1, 5]. However, it differs in that alternative distribution systems can be evaluated. Most studies directed at distribution systems did not consider water quantity [2, 6]. The model removes that limitation, as shown in model application on the Southern High Plains of Texas.

STUDY AREA

Irrigation has become a very significant business in Texas with approximately 8.2 million acres of cropland being irrigated. This total is still rising with the development of new aquifers and improved technology. Since the late 1940's the area known as the Southern High Plains of Texas has become one of the more prominent irrigated agricultural areas of the state.

Irrigation water for approximately five million acres of the Southern High Plains of Texas is pumped from the Ogallala formation [7]. The aquifer is characterized by a small recharge in comparison to the amount of water withdrawn annually. Approximately five million acre feet of water are withdrawn annually, while the amount of recharge ranges from 280 thousand to 933 thousand acre feet [3]. Relating to saturated thickness of the aquifer, the average recharge is from 3/20th to 1/2 inch annually. Thus, withdrawal from the aquifer is 10 to 20 times greater than recharge, giving the Ogallala a characteristic of being an exhaustible water supply.

Irrigation is important to this area since average annual rainfall is only about 18 inches. This means yields are increased four to fivefold for some crops. In fact, soybeans, castors, vegetables and alfalfa are not produced dryland. The major crops are cotton and grain sorghum.

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Available irrigation water in this area ranges from essentially none to 350 feet of saturated thickness [3].[1] About 83 percent of the irrigated acres have less than 200 feet of saturated thickness. Producers across all quantities of water supply are making decisions about irrigation investments. In this area it is critical that quantity of water available be considered in decision-making relative to such things as purchasing a distribution system. Previous studies have shown that quantity of water, magnitude of investment and wage rate significantly affect selection of an "optimum" system [4]. Typically, as the quantity of water available increases, capital investment substitutes for labor; i.e., an optimum irrigation system becomes more capital intensive and requires less labor. The model developed in this study is designed to aid in selecting an appropriate irrigation distribution system.

MODEL

Since the analysis is of an exhaustible natural resource, irrigation water, a temporal analysis is appropriate. Because the study of water use is on both an annual as well as temporal basis, a general recursive program was developed. Recursive in this case is defined to mean that water is allocated annually and each successive years available water supply depends on the quantity withdrawn in previous years.

The model required as input data such things as crop yield per acre, production cost and returns associated with each irrigation level, number of wells, depth to redbed (bottom of aquifer), initial or beginning saturated thickness, discount rate, acres of cropland and acres contributing irrigation water.[2] Since distribution systems are a main focus, other input data are irrigation distribution labor and variable costs (repair, etc.) per acre inch of irrigation water applied.

With these basic data, the model operates to maximize annual net returns.[3] In an analysis, the operation automatically moves to successive years in the water allocation process while recording each annual summary and forcing water use to remain within the continually declining water supply. This process continues through time until the marginal net returns of water are zero (economic exhaustion of the water supply). At the point where net returns with irrigation are equal to net returns produced with dryland production, irrigation is terminated and summary data for the years of irrigation compiled. Returns to irrigation water for each year of irrigation are calculated as the difference in net returns with irrigation and net returns expected with dryland production. These returns to irrigation water are a primary focus of the analysis.

Although the model is a general model developed for applications in regions using an exhaustible water supply for irrigation, there are two functional relationships that can be expected to vary by region. These are well yield and pumping costs. For applying the model to the Southern High Plains of Texas, these functions were of the following form.

Well yield is primarily a function of feet of saturated thickness. After reviewing the literature regarding the nature of the relationship between well yield and saturated thickness, it was decided that an appropriate relationship could be estimated with regression analysis using published observations [3, pp. 24-27].

Of the several alternative functional forms estimated, the one selected as most appropriate and representative of the actual Southern High Plains of Texas situation is:[4]

$$GPM = 2.264\,SA + .0078336\,SA^2 - .0000282\,SA^3$$
$$\qquad (15.46)^* \qquad (3.58)^* \qquad (3.72)^*$$

$R^2 = .995$

$F = 3659.7^*$

Where:

GPM = well yield in gallons per minute, and

SA = feet of saturated thickness or water bearing aquifer.

Due to the nature of the function and data used for the regression, the estimated relationship is applicable only to a maximum saturated thickness of about 250 feet. Well yield declines from about 615

[1] Saturated thickness refers to feet of water-bearing sand. The specific yield of the Ogallala is about 15 percent, or 100 inches of saturated thickness yields 15 inches of water.

[2] Acres contributing irrigation water are expected to exceed acres irrigated since all acres cannot be cropped; i.e., there is water available beneath land used for turn rows, roads and homesteads.

[3] The authors are aware that economic theory indicates that to maximize the present value of an exhaustible resource, an annual use level below that maximizing annual net revenue would be expected. However, due to length of individual planning horizons, interviews, annual liabilities of farmers, previous research and observations, there is evidence that local farmers do strive to maximize annual net revenue. Since the model is designed to aid in farmer decision-making, it is designed to maximize annual net returns. There will, of course, be some exceptions and, for those farmers with a planning horizon of a decade or more, a closer examination of water use among years is needed.

[4] The "t" values are given in parenthesis under the coefficients; * indicates significance at the 0.05 level.

gallons per minute to 250 feet of saturated thickness to 420 gallons per minute at 150 feet, 275 gallons per minute at 100 feet and 130 gallons per minute at 50 feet of saturated thickness. This declining well yield as the aquifer is dewatered, in conjunction with increasing lift, serves to increase pumping costs per acre inch of water.

The second regression equation was developed to give the model a realistic method of estimating pumping cost taking into consideration the decreasing saturated thickness and increasing lift.[5] In the process of literature review, it became increasingly evident that pumping costs were highly variable for a given saturated thickness and lift situation. Although pumping costs were not the principle focus of this study, a close approximation of pumping costs by water resource situation was necessary.

Among the literature reviewed was a publication that listed, for actual observation wells, costs per acre inch pumped and the associated saturated thickness and lift [9, pp. 32-46]. From these data, a functional relationship was estimated between pumping costs and well yield and lift. The equation that was selected for inclusion in the model was:

$$WC = 8.62\, L^{0.65469}\, GPM^{-0.52066}$$
$$\qquad (5.57)^{*} \qquad (10.15)^{*}$$
$$R^2 = .71$$
$$F = 66.37$$

Where:

WC = cost to pump one acre foot of water, and

L = feet from the static water level to the surface.

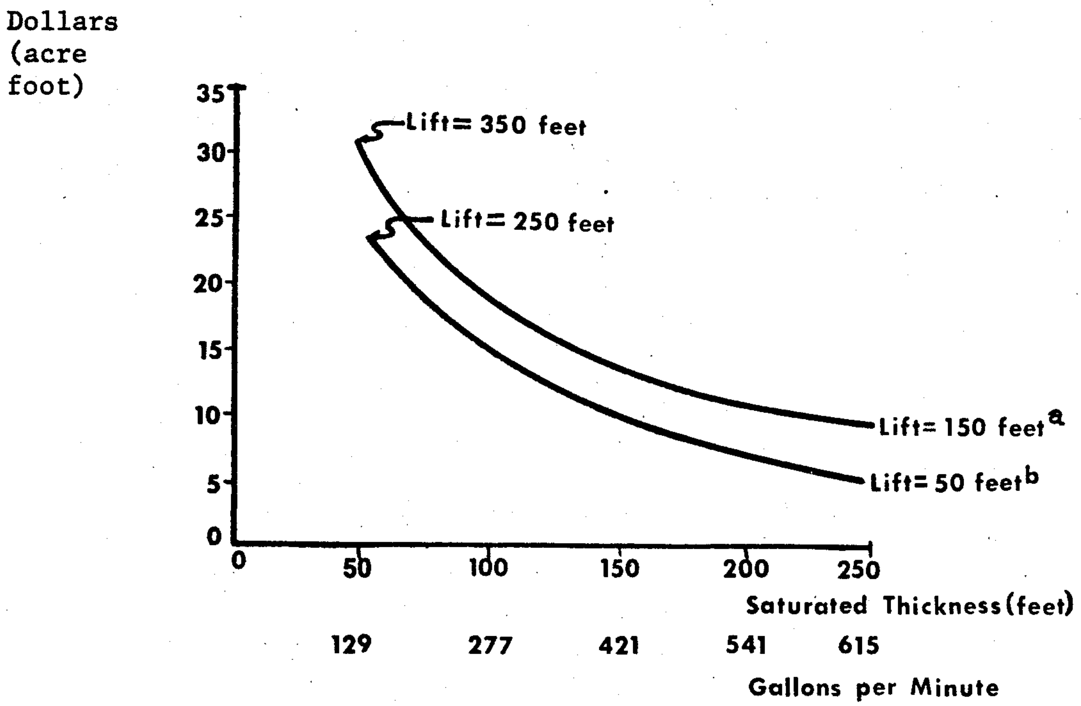

Figure 1. THE EFFECT OF AN INCREASING LIFT AND DECREASING SATURATED THICKNESS ON PUMPING COST PER ACRE FOOT OF WATER, TEXAS HIGH PLAINS

[a]A water resource situation where initial lift is 150 feet. For each foot decrease in saturated thickness, lift is increased one foot.

[b]A water resource situation where initial lift is 50 feet. For each foot decrease in saturated thickness, lift is increased one foot.

[5]Lift refers to the feet between the top of the saturated thickness and the land surface (height water is pumped).

The equation is of the Cobb-Douglas form. The reader will note that as lift increases, costs increase but as gallons per minute increase, costs decrease. In the model application, well yield will be declining and lift will be increasing; i.e., causing pumping cost to increase.

Using the equation, pumping costs can be estimated for most water resource situations in the Texas High Plains. Estimated pumping costs per acre foot of water for alternative well yields and lift situations are presented in Figure 1. With an initial saturated thickness of 250 feet (615 gallons per minute), estimated pumping costs per acre foot are $3.94 and $8.33 for a lift of 50 feet and 150 feet, respectively. When the well yield declines to 200 gpm (75 feet of saturated thickness), pumping costs are estimated at about $18.48 and $23.30 per acre foot of water for a lift of 225 feet and 325 feet, respectively. Expanding beyond Figure 1, pumping costs for a 200 gpm well were estimated at $7.04 per acre foot with a 50 foot lift and $27.46 with a 400 foot lift. This emphasizes the effect of lift on expected pumping costs.

Other equations in the model are identities for the most part, hence, form presents no particular problem. The equations are related such that water is allocated annually with associated costs and returns specified by year.

Input data include, for a specific crop, expected yield and associated production costs for alternative irrigation levels; i.e., one irrigation, two irrigations, etc. Production costs included as input data do not include irrigation labor, water or distribution costs since they are calculated separately in the model.

Incorporated into the model is a check to prevent irrigating acres with an uneconomic level of irrigation. For example, assume returns to irrigation water for a third irrigation are negative. In this case, only those acres that will be irrigated four times are permitted the third irrigation. This assumes the fourth irrigation is profitable.

Operation of the model can be separated into six basic steps: (1) annual analysis is initiated by estimating well yield for the saturated thickness available, (2) pumping costs per acre inch of water are estimated based on well yield and feet of lift, (3) quantity of water available and number of acres that receive each level of irrigation are established, (4) costs and returns are estimated for the year, (5) returns to irrigation water are estimated by subtracting expected farm dryland net returns from total farm net returns and (6) returns to irrigation water are discounted to a present value estimate. The model automatically continues to the next year with the available water supply reduced by the amount used this year. This process continues until the net returns with irrigation are equal to net returns expected with dryland production.[6]

For distribution system fixed costs, this study chose to ignore annual estimates of fixed costs. Rather, initial distribution system investment was subtracted from present value of the water supply (with annual fixed costs of the distribution system not deleted). This, therefore, includes assumptions that the salvage value of the distribution system is very near zero and that the system will last until the water supply is depleted. Based on observations and discussion with those knowledgeable about irrigation in the area, these are not unrealistic assumptions.

Model results are available for each year of irrigation with acres irrigated, costs and returns, total farm net returns, returns to irrigation water and present value of returns to irrigation water indicated. At the termination of irrigation (economic exhaustion of the water supply), present value and years to economic exhaustion of the water supply are presented.

MODEL APPLICATION

For this example of model application to the Southern High Plains of Texas, three irrigation distributing systems were considered. The hand-moved system was least expensive ($5,065) but required the most labor, side-roll system cost $11,539 and used about one-half the labor of the hand-moved while the pivot system cost $22,163 and used about one-fourth the labor of the hand-moved system. Cropped acres were set at 173 with acres contributing irrigation water set at 190 acres.[7] The labor and variable cost of each system, per acre inch of water applied, was taken from published cost studies [2, 6]. Present value of the water supply was estimated using a discount rate of seven percent.

The crop used for this analysis was cotton which sold for $0.27 per pound of lint. The wage rate was set at $2.00 per hour and several water resource

[6]The point where net returns via dryland production are equal to net returns with irrigation is defined as the point of economic exhaustion of the water supply.

[7]Cropped acres were set at 173 because a square field of 173 acres is sufficient to allow a pivot to irrigate 136 acres and 173 acres is appropriate for the other two systems. It was assumed only 90 percent of all acres were cropped -- so for 173 cropped acres there would be 190 acres contributingwater.

Table 1. YEARS OF IRRIGATION AND NET PRESENT VALUE OF THE WATER SUPPLY AT ECONOMIC EXHAUSTION OF THE AQUIFER FOR COTTON BY DISTRIBUTION SYSTEM AND WATER SUPPLY SITUATION; TEXAS HIGH PLAINS[a]

Number of Wells	Irrigation Distribution System	Well Depth and Initial Saturated Thickness					
		125[b]–50[c]		225[b]–115[c]		350[b]–150[c]	
		Year[d]	$1000[e]	Year[d]	$1000[e]	Year[d]	$1000[e]
	I[f]	57	8.67	58	30.63	49	37.42
one	II[g]	59	3.09	60	26.32	51	33.79
	III[h]	--	----	21	1.37	29	12.89
	I[f]	29	13.72	29	41.43	26	46.43
two	II[g]	31	8.55	31	37.98	28	43.74
	III[h]	7	-13.75	21	22.41	26	30.84
	I[f]	19	16.29	21	44.62	19	48.47
three	II[g]	20	11.35	21	41.54	20	46.12
	III[h]	10	- 6.14	19	28.10	25	33.24

[a]Crop price is $0.27 per pound, labor change is $2.00 per hour and discount rate is seven percent. Net present value indicates that distribution system investment has been deleted.
[b]The well depth or depth to redbed.
[c]The initial saturated thickness of the aquifer.
[d]This is the year that economic exhaustion of the water supply occurs for each situation.
[e]The present value of the water supply.
[f]Hand-moved irrigation distribution system.
[g]Side-roll irrigation distribution system.
[h]Pivot irrigation distribution system.

situations were assumed; i.e., well depth ranges from 125 to 350 feet and initial saturated thickness ranges from 50 to 150 feet.

Table 1 presents the estimated present value and economic life for the alternative water supply situations and distributions systems. For each water resource situation (well number, well depth and initial saturated thickness), the hand-moved system was associated with the largest present value of the water supply. As saturated thickness increased for a given number of wells, the difference in the present values of water supply for a side-roll and hand-moved system declined. As larger water supplies were considered, the smaller labor requirement associated with the side-roll system increasingly compensated for the higher investment, compared to the hand-moved system. With a saturated thickness of fifty feet, returns to irrigation more than cover the investment for a hand-moved and side-roll system. The larger investment associated with a pivot system required a saturated thickness of 115 feet or more before the investment could be covered.

Even though the pivot system uses less labor than the other systems, the large investment causes a significant reduction in the present value of the water supply compared to the two other systems. An example of the large investment and its effect can be seen in the irrigation situation with three wells, a saturated thickness of 150 feet and a well depth of 350 feet. The present value of the water supply, before the initial investments were subtracted for the three systems, was within approximately four thousand dollars of each other. The side-roll system was greatest at $57.66 thousand, the pivot system second at $55.40 thousand and finally the hand-moved system was associated with the least present value of the water supply at $53.54 thousand. With the investments in systems deleted, the present values of the water supply were $48.5, $46.1 and $33.2 thousand for the hand-moved, side-roll and pivot system, respectively.

Generally, throughout this area, availability of farm labor is declining, hence, justifying the more capital intensive systems. From 1967 to 1971, the total number of sprinkler systems in operation in the Southern High Plains of Texas increased from 5,697 to 6,461 [7]. At a time when the total number of systems was increasing, the number of hand-moved systems declined from 4,719 to 3,818. The increase in number of systems and replacement of hand-moved systems was due primarily to an increase in the number of side-roll systems. However, it must be noted that several pivot systems were installed during this period.

In addition to distribution system, the effect of the number of wells on the year to economic exhaustion and present value of the water on the 173 cropped acres is important. Table 1 shows that as the number of wells increase, the years to economic exhaustion decrease for the hand-moved and side-roll system. For example, with the initial situation of one well, a well depth of 125 feet and 50 feet of saturated thickness, the years to economic exhaustion for the hand-moved system was an estimated 57. However, when the number of wells was increased to three, the years to economic exhaustion of the water supply declined to 19. Also, it can be noted that for the same situation, the present value to the water supply when one well was used was $8.67 thousand for the 173 cropped acres, but when three wells were used, this present value increased to $16.29 thousand. This same relationship applies to the pivot system but only when the saturated thickness is 115 feet or greater.

These present value figures indicate that three wells are more profitable than one well. However, the technique used in this study (subtracting investment from present value), for distribution systems can also be applied to wells. Basically, this study assumes the wells are already there. If a farmer with 50 feet of saturated thickness and one 125 foot well sees that with three wells, the present value of his water supply doubled (from $8 to $16 thousand) he may wish to add wells. For the situation being used, he would have to add two wells for $8 thousand or less, otherwise the well investment would more than offset any gains to value of the water supply.

Estimates of the present value of water supply are also useful as they relate to productive value of land and water. As the aquifer is dewatered, it is expected farm size will increase. In purchasing additional land, there is the question of how much to pay per acre considering the water supply available. For the farm with a side-roll system, the per acre present value of water pumped with wells was about $230 for 350 foot wells with 150 feet of saturated thickness, $200 for 225 foot wells with 115 feet of saturated thickness and $45 for 125 foot wells with 50 feet of saturated thickness. This means that by paying these amounts for the available water, the farm operator is expected to obtain a seven percent return on his investment by use of the water for irrigation since a seven percent discount factor was used in the calculations. These values apply only when the water is used to irrigate cotton. In addition, this only covers the water component and does not include returns to land. To estimate total productive value per acre, the value of an acre with no irrigation needs to be added to these water value; i.e., value of non-irrigated agricultural land in the area. Based on data used in this study, the productive value per acre of dryland cotton was $170.[8] These values could not apply to a typical farm since it is necessary to consider the effect of other crops, proximity to cities and farm improvements.

To test sensitivity of results, the price of irrigation labor was increased to $4.00. The effect of this higher wage rate was a reduction in present value of the water supply and for the largest water supply (well depth of 350 feet and saturated thickness 150 feet), the present value of the water supply became larger for the side-roll system than for the hand-moved system.

The analysis was also extended to grain sorghum. For grain sorghum, at $2.15 a hundredweight, the results were basically the same except that present value of the water supply was less for each water resource situation.

CONCLUSIONS

Application of the model developed by this study indicates that with adequate labor, the hand-moved distribution system maximizes present value of a water supply. However, present value of the water supply using the hand-moved and side-roll systems are not substantially different and labor scarcity would quickly cause the side-roll system to be preferred.

Present investment required for a pivot system are not offset by labor savings. Only in cases of significant labor scarcity would the pivot system maximize present value of the water supply.

In reviewing the model and results of application, some limitations need to be expressed. The model does not consider a whole farm situation. In the analysis, government programs were not included. Lastly, present value of water, as estimated in this

[8]The $170 per acre is based on rental value of dryland cotton with rent equal to one-fourth of the expected gross revenue. The expected rent would be about $12 per acre, hence the present value of the annual $12 stream of income (rent) calculated at seven percent is $170. The expected rent for non-irrigated land provides an estimate of returns to land.

study, apply only to a single crop (cotton). Over a whole farm situation, the crop mix would affect the present value of the water supply. However, this model provides an improved method for evaluating distribution systems which can be helpful to farmers in selecting an appropriate distribution system and estimating value of the water for a specified resource situation. Regional planners could use the model to estimate the annual effect of a declining water supply on agricultural output and relate this to possible impact on a rural community.

REFERENCES

[1] Harman, Wyatte L., "An Economic Evaluation of Irrigation Water Use Over Time On Texas Farms with a Rapidly Diminishing Water Supply," unpublished Master's Thesis, Texas A&M University, Jan. 1966.

[2] Hughes, W. F., "Irrigation Cost, Center Pivot vs Portable Sprinkler Irrigation System, Texas High Plains," Texas Agr. Exp. Stat. Departmental Information Report 71-1, Jan. 1971.

[3] Hughes, W. F., and Wyatte L. Harman, "Projected Economic Life of Water Resources, Sub-division Number 1 High Plains Underground Water Reservoir," Texas Agr. Exp. Stat. Tech. Monograph 6, Dec. 1969.

[4] Lacewell, Ronald D., "Estimating Distribution Cost of Irrigation Water Drawn from an Exhaustible Aquifer," *Journal of the Society of Farm Managers and Rural Appraisers,* Vol. 35, No. 2 (Oct. 1971), pp. 51-55.

[5] Lacewell, Ronald D. and H. W. Grubb, "Economic Implications of Alternative Allocations of an Exhaustible Irrigation Water Supply," *Southern Journal of Agricultural Economics,* Vol. 3, No. 1, 1971, pp. 149-153.

[6] Lacewell, Ronald D. and W. F. Hughes, "A Comparison of Capital Requirements and Labor Use, Alternative Sprinkler Irrigation Systems, Texas High Plains," Texas Agr. Exp. Stat., Departmental Information Report 71-3, March 1971.

[7] New, Leon, "1971 High Plains Irrigation Survey," Texas Agri. Ext. Service, Nov. 1971.

[8] Pearce, John C., "An Economic Analysis of Alternative Sprinkler Irrigation Distribution Systems on the Southern High Plains of Texas," unpublished Master's thesis, Texas A&M University, Aug. 1973.

[9] Regional Irrigation Research Committee, "Power Requirements and Efficiency Studies of Irrigation Pumps and Power Units," Agricultural Engineering Department, Texas Tech University, Lubbock, Texas, Sept. 1, 1968.