Temporal Implications of Limitations on Annual Irrigation Water Pumped from an Exhaustible Aquifer

Daniel C. Hardin and Ronald D. Lacewell

Economic losses caused by uncontrolled pumping of groundwater is of major concern on the Texas High Plains. A recursive linear programming model is used to evaluate various annual limitations on aquifer depletion. Results indicate that, especially under furrow irrigation, some limitations on groundwater withdrawal could be beneficial to society as well as the producer.

Over 70 percent of the total cultivated acres on the Texas High Plains are irrigated from the underlying Ogallala aquifer. In this region recharge to the aquifer is limited, hence groundwater stocks will eventually become economically depleted for irrigation purposes. This is expected to have a significant impact on the regional economy as farming reverts to dryland production. Previous studies have predicted decreases in the value of agricultural production ranging from 40 to 70 percent resulting from a return to dryland production [Osborn and Harris, Hughes and Harman].

In addressing a problem of management of groundwater, it is important to consider that in Texas, the owner of land is recognized as owning groundwater found therein [Hutchins]. Water rights of this nature give rise to a problem discussed by Bredehoeft and Young. Water withdrawals by one user can not only diminish his own water table, but also draw water from under neighboring land. This, in effect, makes groundwater a common property resource, subject to overexploitation as outlined by Gordon. However, residents of the Texas High Plains recognized such a problem and, in the early 1950's, established underground water conservation districts [Anderson]. These districts, provided for by Texas law, have established a strict set of regulations and standards governing well spacing. In addition, research related to the Ogallala aquifer in the study region indicates that the lateral movement of water is at an extremely slow rate, i.e., 2 inches per day [Cronin]. The slow lateral rate of water movement and well spacing restrictions minimize the problems of user interdependence and commonality of water resource use.

A major issue for individual farmers is temporal allocation of their underground water supply to maximize returns to the water. Farmers make many short-run decisions because they are concerned with next year's income. This may suggest to some that farmers use a short time horizon for planning

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water use. However, the creation of the water districts suggests that most farmers are concerned with the future value of their land as well as current income flow. Whether or not it is economic for a producer to attempt to lengthen the life of the water supply by practicing water conservation depends implicitly on the choice of discount rate. Producers who perceive higher interest rates are less likely to practice conservation, other things being equal.

From a regional and societal viewpoint, the conflict between private and social discount rates must be faced. An underground water supply, to a degree, benefits all of society, not just the farmer whose land lies above. The use of high discount rates could prevent distribution of income to the future generations which might be deemed desirable by present generations [Eckstein]. Conversely, the individual producer who has the opportunity to invest capital in earning assets would not accept the concept of a low discount rate which encouraged water conservation without institutional restrictions or economic incentives. Previous studies for the area [Hardin, et al.; Hardin and Lacewell] have revealed economically viable improvements in water usage efficiency which will extend the life of the water supply. Institutional restrictions on water usage, however, have not been addressed.

It is beyond the scope of this study to determine the appropriate rate to be used to discount future income streams. However, it is possible to determine a "break-even" discount rate which will equate the present value of two streams of net income generated from limited versus unlimited groundwater withdrawal.[1] This paper examines the effects on the economic life of the water supply and computes break-even discount rates for unlimited versus various limited annual rates of water withdrawal on the Texas High Plains.

[1]This will be equivalent to the internal rate of return for the limited case, where the net return stream generated by unlimited withdrawal is considered an opportunity cost and is netted out each year.

Methodology

This study is comprised of two primary components. First, a recursive linear programming model is used to develop annual farm plans and streams of net returns for selected annual rates of groundwater use.[2] Secondly, a procedure is developed to estimate the discount rate which equates the present value of two streams of net returns.

Recursive Model

The recursive linear programming model is based on a typical farm situation on the Texas High Plains. The model includes the major crops in the area (corn, grain sorghum, soybeans, cotton and wheat) under all applicable dryland and irrigation options. A total of 59 production activities are included.

Crop enterprise budgets developed by area economists of the Texas Agricultural Extension Service for the 1978 crop year were the basis for developing the model coefficients. [Extension Economists — Management]. Yield data for alternative irrigation levels were taken from statistical production functions estimated for the area [Shipley 1977a]. Furrow irrigation production functions were adjusted for sprinkler irrigation in the study area to reflect a reduction in water use of 33 percent to attain each yield level [Shipley 1977b]. Shorter row lengths and prudent changing of irrigation sets would significantly affect water use with a furrow system. More efficient distribution of irriga-

[2]Previous studies of intertemporal groundwater allocation have used dynamic programming (e.g., Burt), where an optimal path of depletion is developed. Another major approach has been in determining yearly depletion based on maximization of annual net returns, as used by Bredehoeft and Young. The computational model used in this study is of the latter type, originally developed in earlier studies by the authors and slightly modified for this application. Dynamic programming as a computational form was considered originally, but rejected, as it was felt that the increase in accuracy would not sufficiently offset the associated higher solution cost, particularly considering the original purposes of the model.

tion water was not investigated in this particular study. Target prices for 1978 were used for all crops.

Irrigation applications and water availability are divided into 10 periods; one for January-February, one for November-December, and one for each of the other months. The upper limits of water availability are established to reflect the maximum amount that can be pumped in each time period, based on well yield in gallons per minute, number of wells and average number of days in each period not used for well repairs and maintenance. In addition, an artificial restraint is imposed limiting the total amount of water pumped during the year. This restraint places an upper limit on the yearly decline in saturated thickness[3] of the aquifer.

For the long run analysis presented here, fixed costs, which included depreciation, insurance, taxes and opportunity cost, are subtracted from returns. Fixed costs for machinery and equipment and for irrigation distribution systems are charged on a per acre basis in the LP model, with machinery and equipment fixed costs varying according to the level of irrigation. Fixed costs of irrigation wells and pumping plants are charged on an annual basis. Pumping plant fixed costs are adjusted depending on well yield and pumping lift. There is an implicit assumption that adjustments in the pumping plant occur, with old equipment sold for its salvage value.

The LP model is established in a recursive framework and incorporates a Fortran subroutine which modifies the LP model after each year's solution to reflect the farm situation for the following year. This updating procedure is performed as follows:

(a) Calculates the decrease in saturated thickness of the aquifer and associated increase in pumping lift based on the amount of water withdrawn in the previous year.
(b) Calculates the change in well yield, if any, based on the change in saturated thickness.
(c) Calculates the amount of irrigation fuel required to pump an acre-foot of water based on the adjusted pumping lift.
(d) Calculates the maximum acre-feet of water which can be pumped in each time period based on the adjusted well yield and for the entire year based on the specified limit on withdrawal from the aquifer.
(e) Stores the future value of net returns to the farm plan for later use in calculation of break-even discount rates.
(f) Modifies the LP tableau with new irrigation water upper limits and irrigation fuel requirements.

The equations used in the Fortran program are described in the following paragraph, with all coefficients relating to the current time period unless otherwise denoted by subscript. Decline in saturated thickness of the aquifer is represented by

$$D = W_{t-1}/(.15 * CA) \qquad (1)$$

where

D = decline in saturated thickness of the aquifer [Wyatt, et al.]

W_{t-1} = acre-feet of water pumped in the previous year

CA = acres contributing to the aquifer (including non-cultivated acres and dryland)[4]

$.15$ = coefficient of storage for the Ogallala aquifer.

Maximum well yield is assumed to remain constant for all levels of saturated thickness above 207.9 feet [Reddell], represented by

[3] Saturated thickness refers to feet of water-bearing sand. The coefficient of storage of the Ogallala is about 15 percent, or 100 feet of saturated thickness yields 15 feet of water [Cronin].

[4] 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.

equation (2). Equation (3) represents the well yield relationship for lower levels of saturated thickness [Johnson]. This relationship between well yield and saturated thickness of the aquifer is representative of the region for an average well and is much less than the maximum yield potential of the aquifer [Reddell].

(2) $GPM = GPM_0$ if $ST \geqslant 207.9$ feet

(3) $GPM = 1.14 * (ST/250)^{.71} * GPM_0$ if $ST < 207.9$ feet

where

- GPM = current period well yield in gallons per minute
- GPM_0 = original or maximum well yield based on the size of the well, with 800 GPM typical
- ST = saturated thickness of the aquifer in the current time period.

The amount of natural gas required to pump water is given by

(4) $NG = .044L + .102\ PSI$

where

- NG = natural gas in thousand cubic feet required to pump one acre-foot of water [Kletke, et al.]
- PSI = water pressure required, in pounds per square inch
- L = pumping lift.

Water availability by critical time period is established as follows:

(5) $M = .0044 * GPM * T$

where

- M = maximum acre-feet of water that can be pumped in a specified period by one well
- T = days available for pumping in a specified time period
- .0044 = constant value which translates gallons per minute into acre-feet per day.

The limitation of annual decline in saturated thickness is expressed through a rearrangement of equation (1).

(6) $WMAX = .15 * CA * DMAX$

where

- WMAX = maximum acre feet of water that can be pumped in the year
- DMAX = maximum annual decline in saturated thickness of the aquifer (in feet).

Discounting Procedures

The break-even discount rates used in this study were calculated by solving the following equality:

(7) $$\sum_{t=1}^{g} \left[\frac{NR(U)_t}{(1 + d)^t} \right] = \sum_{t=1}^{h} \left[\frac{NR(L)_t}{(1 + d)^t} \right]$$

with the discount rate of the form:

(8) $d = [(1 + r)/(1 + i)] - 1$

where

- NR = annual net returns to water
- U = unlimited groundwater withdrawal
- L = limited groundwater withdrawal
- g = year of economic exhaustion of the water supply in the unlimited groundwater withdrawal situation
- h = year of economic exhaustion of the water supply in the limited groundwater withdrawal situation
- r = nominal discount rate including inflation, risk and the real time

value of money [Watts and Helmers]

i = rate of inflation [Watts and Helmers].

Farm Situation

Center pivot sprinkler and furrow irrigation systems were considered separately.[5] In each case, four applications of the model were made. A maximum rate of development was established, placing no annual limitation on water withdrawal, along with a case of "limited conservation," in which the decline of the water level was restricted to four feet per year. In both cases, four irrigation wells were assumed available for the farm. Two rates of further conservation were considered, limiting annual saturated thickness decline to three and two feet per year, respectively. In these applications only two wells were available. The annual water limitations removed the need for two of the four wells until far into the time horizon. Thus, the cost of the additional wells in the early years outweighed their benefits in later years.[6]

The analysis was based on 640 cultivated acres. For the 640 acres, two men were assumed available for all farm operations except hoeing, e.g., tillage and irrigation. Labor periods were established in the model and, based on total hours the two men (owner-operator and one full time employee) had available in each period, a labor restriction was imposed. With greater irrigation water and labor requirements for furrow irrigation, the labor restriction is important to furrow irrigation solutions.

[5]The two types of systems are not considered directly competitive since the sprinkler systems are primarily on more sandy soils and/or undulating terrain while furrow or gravity flow systems are predominately on more hardland soils.

[6]Applications of the model were made with four wells. For the two and three foot annual decline of the water level, the added cost caused earlier economic exhaustion of the water supply and yielded returns to water less than for the unrestrained annual water use level.

The aquifer for the farm was assumed to have an initial saturated thickness of 250 feet and depth to the water or pumping lift of 250 feet. To estimate returns to the groundwater resource, it was first necessary to establish returns to land. This was achieved by applying the linear programming model with only dryland crop alternatives. This provided a dryland cropping pattern and an estimate of annual net returns of $17,870. This was netted out each year in order to obtain annual returns to water.[7]

Results

Table 1 shows years of irrigation, aquifer and irrigation characteristics, returns to water and break-even discount rates for all analyses. In choosing a "required" rate of return for comparison with the break-even discount rates presented, only elements which reflect risk and the true time value of money should be considered. For this analysis a time value of 1.5 percent [Reneau, et al.] is assumed. The discussion then centers on the difference between this and the break-even rate, and whether or not this difference is sufficient to account for risk.

Sprinkler Irrigation

Sprinkler irrigated land is planted to grain sorghum. All crop acres are irrigated, except the corners of the field which cannot be reached by the center pivot system, for unlimited groundwater withdrawal and the four foot annual decline limitation, as shown in Table 1. The more restrictive limitations on groundwater withdrawal (two and three feet decline annually) cause a reduction in initial irrigated acres.

As saturated thickness declines due to continued pumping, well yields decline and eventually the initial year irrigated acreage

[7]Since a cost for management was not explicitly considered, the returns to land are more accurately defined as returns to land and management of dryland cropping. Thus, in this analysis, the returns to water also include returns to irrigation management.

TABLE 1. Effects of Alternative Annual Limitations on Groundwater Withdrawal for Irrigation.[a]

		Maximum Annual Water Level Decline (feet)			
Item	Units	2	3	4	Unlimited
Sprinkler					
Initial year characteristics:					
Land Irrigated	Acres	276	414	533	533
Irrigation water applied	Acre-Feet	276	414	552	667
Years initial irrigated acreage maintained	Years	86	38	44	38
Year irrigation ceased	Years	122	97	61	55
Ending saturated thickness	Feet	26.4	26.8	26.1	25.5
Total returns to water (undiscounted)	Dollars	1,532,145	1,231,964	1,022,662	921,233
Break-even discount rate (as compared to unlimited)	Percent	.5	4.5	5	
Furrow					
Initial year characteristics:					
Land Irrigated	Acres	301	326	442	461
Irrigation Water applied	Acre-Feet	276	414	552	732
Years initial irrigated acreage maintained	Years	28	15	32	10
Year irrigation ceased	Years	110	78	55	51
Ending saturated thickness	Feet	31.5	31.6	38.5	37.2
Total returns to water (undiscounted)	Dollars	699,374	785,425	585,898	537,777
Breakeven discount rate (as compared to unlimited)	Percent	1	11.5	6.5	

[a]The analysis is based on a typical Texas High Plains farm with an initial 250 feet of saturated thickness and 250 feet of lift. Labor restraints include the owner-operator and one full-time employee. The furrow irrigation system was assumed to irrigate one-half mile length rows. The sprinkler system uses 33 percent less water than a furrow system for any specified yield level.

must decline. However, the effect of the annual limitation on pumping dramatically affects the number of years before irrigated acres begin to decline. For example, original irrigated acreage remains constant for 86 years in the case of the two foot limitation compared to 37 years for both the three foot decline and for the unlimited annual withdrawal. With a four foot limitation, original irrigated acreage holds constant for 44 years, even though it is the same acreage as in the unlimited case. This is due to the elimination of one post-plant irrigation in the later years. Compared to unlimited annual water use, the two and three foot limits on annual decline of the saturated thickness extends the life of the water supply significantly (67 years and 42 years, respectively) as opposed to the four foot limitation, which added only six years of irrigation.

The break-even discount rates were 0.5, 4.5, and 5 percent for the two, three and four foot maximum annual levels of saturated thickness decline, compared to annual unlimited withdrawal of irrigation water. At higher discount rates than these, the unlimited withdrawal of groundwater results in a greater present value of the water supply than the respective limited withdrawal rate.

The two foot withdrawal rate would not be competitive for the producer or society, since it does not cover the assumed 1.5 percent time value of money. The individual producer would prefer the three or four foot withdrawal rates only if his perceptions of risk were less than 3 and 3.5 percent, respectively. Society as a whole, which would likely consider little or no risk, would probably prefer both situations of conservation to unlimited withdrawal.

Furrow Irrigation

Cropping patterns vary widely under furrow irrigation. The labor restriction impacts heavily on furrow irrigated acreage causing a maximum of 461 of the possible 640 crop acres to be irrigated, as shown in Table 1. Beginning farm plans, in general, include cotton, wheat and grain sorghum with some acreage shifting to soybeans in later years. Increased water requirements for furrow irrigation result in rapid changes, with initial irrigated acreage beginning to decline after as little as ten years in the case of unlimited withdrawal. Irrigated acreage remains constant for the first 32, 15 and 28 years given the four, three and two foot limitations, respectively. Again the limitation of four feet of annual saturated thickness decline results in only a slight increase (4 years) in the life of the water supply, while at two and three feet the increases are much more substantial (59 and 27 years, respectively).

Break-even discount rates for two, three and four foot limitations on annual saturated thickness decline were 1.0, 11.5, and 6.5 percent, respectively. The three foot limitation shows a higher discount rate than the four foot limitation due to the elimination of two wells. Again, the limitation to two feet of decline per year does not show sufficient return to be considered by producers or society. However, both groups would likely prefer either the three or four foot limitations to unlimited withdrawal (unless, in the case of the four foot limit, the producer requires a risk premium greater than 5 percent).

Conclusions

The eventual economic exhaustion of the Ogallala aquifer has been a major concern of research efforts in the Texas High Plains for many years. The economy of the region will be severely affected when the area is forced to revert completely to dryland farming. The research effort presented here has attempted to quantify the effects on producer returns to water of water use limitations which reduce profits in the short run but extend the life of the water supply.

Determination of an optimal rate of water withdrawal depends on the interest rate chosen. The results indicate that both producers and society as a whole could benefit if some annual limitation was imposed on withdrawal of water to be applied under furrow irrigation. However, limitation of annual water decline may not be economically viable from the standpoint of the producer who operates with sprinkler irrigation. The situation for sprinkler irrigation could be reversed if a lower interest rate, perhaps more indicative of the preferences of society, were chosen.

A limitation on annual aquifer withdrawal rates for irrigation would provide strong incentives to adopt more water efficient technology involving equipment and field patterns. This study raises some questions relative to an appropriate temporal allocation of water from an exhaustible aquifer. The issue arises of appropriate institutions, be they regulatory or economic, which provide the framework and incentives to modify annual withdrawal rates with an objective of maximization of the value of a limited and exhaustible resource. Of course, the issue of appropriate discount rates for maximization of the groundwater value as well as implications on viability of the farm firm must be addressed.

References

Anderson, Don. "Critical Issues Facing the High Plains Crop Producers." Proceedings of the Texas A&M University Centennial Year Water for Texas Conference, Texas Water Resources Institute, March 1976.

Bredehoeft, John D. and Robert A. Young. "The Temporal Allocation of Ground Water — A Simulation Approach." *Water Resources Research*, 6(1970):3-21.

Burt, Oscar R. "Intertemporal Control of Ground Water in Multiaquifer Models." Staff Papers in Economics, No. 76-28, Montana State University, Bozeman.

Cronin, J. G. "A Summary of the Occurrence and Development of Ground Water in the Southern High Plains of Texas." Texas Board of Water Engineers, Bulletin 6107, September 1961.

Eckstein, Otto. *Water Resource Development: The Economics of Project Evaluation.* Harvard University Press, Cambridge, Massachusetts, 1958.

Extension Economists-Management. "Texas Crop Budgets." Texas Agricultural Extension Service MP-1027, 1978.

Gordon, H. Scott. "The Economic Theory of a Common-Property Resource: The Fishery." *Journal of Political Economy*, 62(1954):124-142.

Hardin, Daniel C. and Ronald D. Lacewell. "Implications of Improved Irrigation Pumping Efficiency on Farmer Profit and Energy Use." *Southern Journal of Agricultural Economics*, 11(1979):89-94.

Hardin, Daniel C., Ronald D. Lacewell and James A. Petty, "The Value of Improved Irrigation Distribution Efficiency with a Declining Groundwater Supply." Texas Agricultural Experiment Station TA-14294, May 1978.

Hughes, William F. and Wyatte L. Harman. "Projected Economic Life of Water Resources, Subdivision Number 1 High Plains Underground Water Reservoir." Texas Agricultural Experiment Station Technical Monograph 6, December 1969.

Hutchins, Wells A. "Water Rights Laws in the Nineteen Western States." Natural Resource Economics Division, Economic Research Service, United States Department of Agriculture, MP-1206, 1974.

Johnson, Edward E., Inc. *Groundwater and Wells.* St. Paul, Minn., 1966.

Kletke, Darrel D., Thomas R. Harris and Harry P. Mapp, Jr. "Oklahoma State University Irrigation Cost Program, User Reference Manual." Oklahoma State University, Department of Agricultural Economics, Research Report P-770, May 1978.

Osborn, J. E. and T. R. Harris. "Interindustry Effects of a Declining Groundwater Supply." Texas Agricultural Experiment Station, B-1134, June 1973.

Reddell, Donald L. Personal communication, April 25, 1978.

Reneau, D. R., C. R. Taylor, B. L. Harris, R. D. Lacewell and P. E. Mueller. "An Economic Analysis of Erosion and Sedimentation in Lower Running Water Draw Watershed." Texas Water Resources Institute, TR-90, May 1978.

Shipley, John. "Economic Considerations in the Irrigation of Grain Sorghum and Corn, Texas High Plains." Texas Agricultural Experiment Station TA-13840, December 1977a.

Shipley, John. Personal communication, December 20, 1977b.

Watts, Myles J. and Glenn A. Helmers. "Inflation and Machinery Cost Budgeting." *Southern Journal of Agricultural Economics*, 11(1979):83-88.

Wyatt, A. Wayne, Ann E. Bell and Shelley Morrison. "Analytical Study of the Ogallala Aquifer in Deaf Smith County, Texas." Texas Water Development Board Report 213, July 1977.