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Estimated Farm Level Benefits of Improved Irrigation Efficiency

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INTRODUCTION

There are about 15 million acres of cropland in the U.S. that are irrigated from aquifers which are incurring declining water levels (Sloggett). This is primarily in the Great Plains Region where irrigation water is pumped from the Ogallala Aquifer. Mining from the aquifer is estimated at 14 million acre feet per year (Frederick and Hanson). The declining groundwater supply increases pumping lift and reduces well yields.

Concurrently, there has been a dramatic increase in the cost of energy for pumping since 1973. For example, in the Trans Pecos Region of Texas, natural gas prices increased 450% from 1972 to 1975. Energy has become one of the most important factors in irrigated crop production. A 1975 study showed that 53% of the total variable costs of producing corn in the Great Plains was energy related (Skold).

The sensitivity of irrigated agriculture to increased fuel costs and declining groundwater levels has provided incentives for irrigated farmers to investigate alternative crop rotations and opportunities to improve irrigation water pumping and distributional efficiencies. The emphasis of this report is to estimate the value to an irrigated farmer on the Texas High Plains of improving irrigation water distribution efficiency.

One means of improving the water use efficiency is to implement water conserving techniques. The main purpose of these techniques is to maximize crop production by minimizing the amount of water lost through the production systems. The major sources of water loss in a crop production system are runoff, percolation, and evaporation. Examples of water conserving techniques include terracing, furrow dams, reduced tillage, and crop rotations. In addition, improved irrigation application techniques can enhance the efficiency of water used for irrigation in the region. On-farm irrigation efficiency statewide for Texas has been estimated between 60 and 70% (Wyatt,1981). The implementation of advanced irrigation application techniques could potentially increase this efficiency up to 98% (Lyle & Bordovsky,1980).

Furrow irrigation and sprinkler irrigation are the two major irrigation systems currently in use. Techniques designed to improve furrow efficiency include alternate furrow irrigation, furrow diking, and surge flow. Alternate furrow irrigation improves the timeliness of irrigation applications and increases lateral water movement thereby reducing deep percolation losses. Alternate furrow irrigation can be used with furrow diking or row dams on non-irrigated furrows to reduce rainfall runoff and soil erosion. The surge flow technique delivers large surges of water into the furrow on an intermittent cycle to reduce percolation losses at the upper end of the field.

Sprinkler irrigation is the second major distribution system used for crop production primarily on mixed and sandy soils in the region. The use of these systems have increased tremendously over the past 25 years. This growth in the use of sprinkler irrigation systems is reflected in the increase for Texas from 668 thousand acres in 1958 to 2.2 million acres in 1979 (Texas Department of Water Resources). With the rapid rise in the relative price of energy during the 1970's, the emphasis of improving sprinkler efficiency has focused on both reducing their energy requirements and decreasing the amount of water lost through evaporation.

One system which has been developed to meet these needs is the L.E.P.A. system or Low Energy Precision Application system (Lyle and Bordovsky,1980). This system operates by distributing water through drop tubes and low pressure emitters directly into the furrow as opposed to high pressure systems which utilize overhead sprinklers to distribute the water. In field trials of the LEPA system, measured application and distribution efficiencies averaged 98% and 96% respectively (Lyle et al., 1981).

Objectives

Within the problem environment described above, the objective of this study is to identify the economic benefits to the farmer of improving irrigation efficiency on the Texas High Plains region. Given exogenously set input supply prices and commodity demands, certain irrigation techniques may be more profitable than others.

This study will concentrate on identifying those alternatives which are economically optimal from the producers standpoint, that is, those techniques which maximize the present value of net revenue over a twenty year planning horizon under different output price scenarios and initial groundwater situations.

The Study Region

The Texas High Plains encompasses approximately 35,000 square miles in 42 counties. The regional economy is highly dependent on the agricultural production of cattle, cotton, wheat, and feed grains. Farm and ranch land comprise over 96% of the total land use in the area while cropland accounts for 42% or 9.4 million acres in the region. From 1972 to 1981, regional crop production averaged 40% of the state's total crop production receipts. In addition, crop production is a significant basis for the High Plains economy. In 1981, crop production accounted for 61% of the total agricultural cash receipts in the region (Texas Crop and Livestock Reporting Service,1972-1981a). Crop production in the High Plains during 1981 accounted for 1.69 billion dollars or approximately 40% of the value of the states total crop production receipts.

The climate of the study area can be characterized as semiarid or a relatively low and erratic rainfall pattern with a wide variation in daily and seasonal temperatures. Annual rainfall in the region averages approximately 19 inches with recorded ranges from 8 to 31 inches. The distribution of rainfall is variable with intense local showers occurring during the summer months. The average monthly temperature in the region ranges from 21° F in January to 91° F in July with recorded extremes from -10° to 115° F. Other significant climatic factors include a relatively low humidity rate and seasonally high wind velocities. The interaction of these two factors increase the potential evaporation rate in excess of annual percipitation rates.

Due to the limited rainfall, crop yield and crop rotations are severly limited in the region unless irrigation water is utilized. Although irrigation is not absolutely essential for crop production, it allows for greater production intensity, increased average yields per acre, and reduces the variability in crop yields due tc seasonal drought.

The principal source of irrigation water on the High Plains is pumped from the underlying Ogallala aquifer. The Ogallala is characterized as an extensive aquifer having a limited recharge rate with a substantial variation in surface distance, saturation thickness, and storage capacity. In Texas, the aquifer underlies approximately 20 million acres with an estimated capacity of 340 million acre-feet of water (Muller and Price, 1974). Due to the spatial distribution of water in the aquifer, only 282 million acre-feet are considered technically recoverable. The aquifer receives a negligible amount of recharge which has been estimated between 1/2 to 1 inch per year (Wyatt,Bell,and Morrison,1976). Projected average annual rates of decline in the static water level range from .35 to 4.08 feet depending on the climatic factors and the local saturation thickness (Wyatt, et al.). Due to the geological formation of the Ogallala in Texas, the aquifer can be divided into two seperate hydrologic units. As a result of the hydrological characteristics, the study region represented in Figure 1 can be subdivided into the Northern and Southern High Plains.

Irrigation technology was first introduced on the High Plains as early as 1911. However, it was not until the 1950's when irrigated acreage increased significantly due to previous droughts coupled with easily attainable financing and improved pumping equipment. Irrigation development reached a peak during the 1974-1977 period. In 1976, there were approximately 77,000 irrigation wells on the High Plains. Since then, the number of productive irrigation wells in the Northern High Plains has declined from 35,000 in 1976 to 32,500 in 1980 (Texas Crop and Livestock Reporting Service, 1981).

Even though irrigated acreage has declined recently, irrigated crop production continues to be a vital component of the regional and state economy. Currently 6 million acres or 50% of the cropland in the High Plains region is irrigated annually (Texas Dept. of Water Resources,1981).

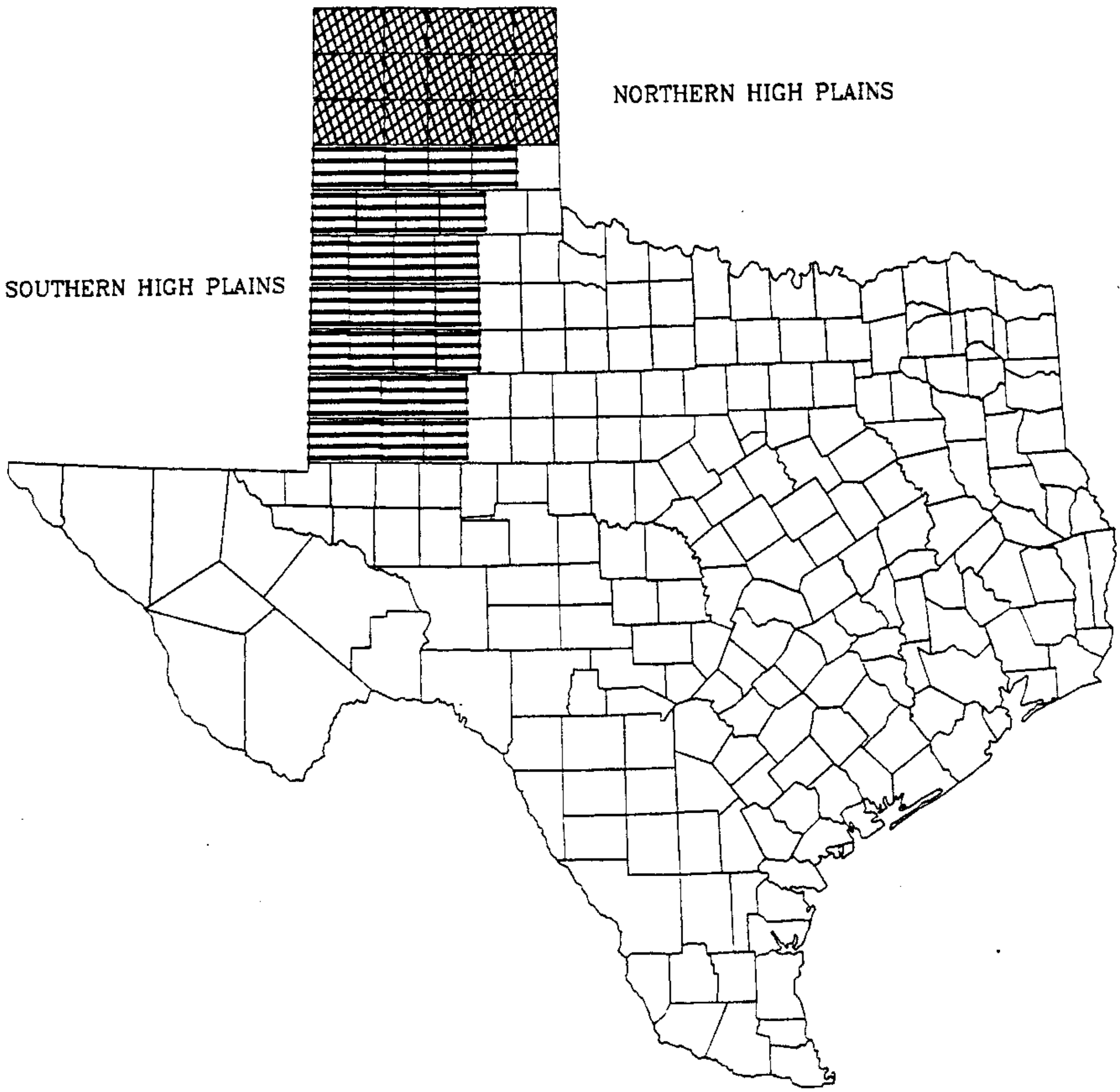

Figure 1. The High Plains Study Area

The significance of this crop producing region is reflected in the percent contribution to the states total crop output over the past ten years. Annual average cotton production in the region accounted for 3 million acres or 55% of the states cotton output. Similiarly, 2.8 million acres of wheat and 2.3 milion acres of sorghum were produced annually in the region. These figures represent 53% and 44% of the state's annual wheat and sorghum production.

Previous Studies

With declining water supplies and rising energy prices, several studies have addressed the effect of energy price on irrigation in the Texas High Plains. This review addresses only a few. Breakeven relationships between product and irrigation fuel prices were estimated for natural gas (Hardin and Lacewell,1977). At that time, the study suggested a very narrow profit margin for all crops except cotton. A regional study indicated fairly small energy price rises with no change in crop prices would cause significant cropping pattern change (Lacewell, Condra, and Fish). Petty, et.al. in a 1980 study showed a dramatic reduction in the economic life of the Ogallala aquifer if energy prices continue to rise faster than crop prices. The decline in the groundwater level coupled with a rise in the relative price of energy has significantly increased the cost of irrigated crop production. This rise in production cost reduces the profitability of irrigated agriculture in the region. The Petty, Lacewell, Hardin and Whitson study indicated that a short-run increase in the price of natural gas above $7.85 per mcf would result in a complete shift from irrigated to dryland for a typical High Plains farm even with good groundwater availability. In addition, this study found that long-run annual returns above variable and fixed costs were reduced by more than 30% when the price of natural gas was increased annually by $.25 per mcf from a base of $1.50 mcf. Thus, energy prices appear to be a very effective water conservation factor.

The need for physical and economic efficiency became paramount. Hardin and Lacewell (1981) investigated wind as an alternative energy source for pumping water. The cost of the machinery in 1981 was greater than the savings in purchased energy. Reneau, Lacewell, and Ellis investigated the impact of new irrigation technology on the Texas High Plains. This study provided estimates of the value of one irrigation technology as compared to another. However, a major limitation of the Reneau, Lacewell, and Ellis study was the value to a farmer of upgrading the efficiency of a current system or shifting systems for greater efficiency. Hence, this study could not be applied by an individual farmer. It is this gap which we purpose to cover in this report.

PROCEDURES

Basically this work applied the Reneau model under alternative irrigation distribution system efficiencies to estimate the change in farmer's returns above variable costs. However, regional and water resource delineation was required as well as the specification of the cost and price data. The analysis was based on a 20 year period and fixed costs were ignored. Thus, the benefits derived for improved irrigation distribution efficiency do not account for any costs incurred to achieve the improvement in efficiency. Rather, the estimates are a measure of the maximum that an irrigated farmer could expend to improve distribution efficiency.

Model

To evaluate the benefits of improving irrigation efficiency as it relates to crop production in the High Plains region requires a large amount of detailed information and an analytical procedure or model. The analytical procedure employed in this analysis is the recursive linear programming model developed by Reneau. Unlike a linear programming model, the recursive model allows for the revision of the objective function, the coefficient matrix, the level of constraints, or any combination thereof based on the solution in time period 't' and conditions which prevail in time period 't+1'.

The recursive programming model used in this study can be characterized as a three component system. The first component is the optimizing operator which describes the dependence of specific choice variables on the objective constraint functions which inturn depends on the input data. The second component is the data operator which defines how the data entering the objective and constraint functions depend on the current conditions of the entire system. The final component of the model is the feedback operator which specifies the succeeding state of the system which is dependent upon the current condition and the current optimal decision variable levels.

The crop production activities incorporated in the recursive programming model are based on a one acre land unit. Required inputs for land preparation, planting, and crop protection are defined on a per acre basis reguardless of crop yield (Reneau,Lacewell,and Ellis,1984). Input useage does vary across crops and cropping intensity. The amount of other inputs such as fertilizer, irrigation water, and custom harvesting will depend on expected yield. Table A-1 and A-2 list the level of inputs required by crop and the fertilizer and harvesting equations, respectively. Fertilizer application rates were set to maintain soil fertility levels for the majority of soils in the region. Harvesting and hauling costs were based on custom rates in the area.

Water requirements per irrigation were derived assuming a pre-plant delivery rate of 6 inches and a post-plant delivery of 3 inches. These base requirements are then translated into total water applied by considering factors such as tillage affects on water use and the application efficiency of the irrigation system. Once the total water application is derived, per acre inch charges for water pumped can be calculated using the distributed cost schedule listed in Table A-3. In addition to the per acre inch charge, well, pump, fuel, and maintenance and repair costs are derived for each system.

Fixed costs for the furrow distribution system include gated pipe, hydrants, end plug, gate valves, and the main pipeline. The fixed cost for improved furrow also includes a recirculation pit and plumbing. Sprinkler system costs are based on a standard center-pivot with mainline, pad, control and drives (Reneau,Lacewell,and Ellis,1983). The fixed cost for the LEPA system includes the additional cost of pressure regulators,drop tubes, and spray emitters.

The variable costs for irrigation systems consist of fuel for pumping, labor, and repair and maintenance costs. The fuel cost for pumping is calculated by utilizing the formula for natural gas powered pumps by Kletke, Harris, and Mapp (1978). The price of natural gas and pump efficiency are set at the beginning of each iteration of the model. Labor for irrigation is calculated as required distribution labor and 5% is added for pump and well maintenance. The total fixed cost per acre inch of water pumped is the sum of the fixed cost for the well, the pump, and the distribution system.

To generate the production activities for each iteration of the model, a sequence of steps are required. The first step is to read the input data which defines a particular resource scenario. After the input data is read, land classes are generated and held constant throughout each iteration of the model.

Price levels for each simulation are derived by updating the internally stored price base. The price of natural gas, diesel, nitrogen, phosphorus, and labor were set at the average 1982 base price level for the region. Commodity prices were calculated by taking 20 years of seasonally adjusted prices and the parity price index (U.S.D.A.) to state these prices in terms of 1982 dollars. Table 1 lists the internally stored average price data for both inputs and commodities. Also shown in Table 1 is the alternative price level used to test the models sensitivity to expected prices. The alternative price level represents the lowest commodity prices in the 20 year price series expressed in terms of 1982 dollars.

The program then generates production activities for each time period by looping through all possible cropping combinations, irrigation distribution systems, tillage practices, and land classes. In the model

Table 1. Input and Commodity Price Levels

Item	Unit	Average Price[a]	Alternative Price[b]
		($)	($)
Commodity			
Cotton	lb	.74	.48
Corn	bu	3.95	3.00
Grain Sorghum	cwt	5.95	4.52
Soybean	bu	8.08	5.58
Wheat	bu	4.71	3.25
Wheat Grazing			
Dryland	ac	9.00	6.84
Irrigated	ac	36.00	27.36
Inputs			
Natural Gas	mcf	3.85	8.86
Diesel	gal	1.16	
Nitrogen	lb	.28	
Phosphorus	lb	.30	
Labor	hr	5.00	
Interest on Capital	apr	10.00	

[a] Average commodity prices are the average price recieved from 1962-1981 expressed in 1982 dollars through the parity price index.

[b] Alternate commodity prices are the lowest annual price recieved from 1962-1981 expressed in 1982 dollars.

Source: Reneau,Lacewell,and Ellis (1983).

developed for this study, net returns are maximized subject to various resource constraints. The first of these constraints is land by soil type. Since the amount of acreage available by soil type in the region is limited, this constraint forms the righthand side value for each soil type in the LP matrix.

The second set of constraints in the model control the quantity of irrigation water available in each irrigation period and over the entire study period. The quantity of water which can be pumped during a single time period will depend on the number of producing wells, average well capacity, saturation thickness, pump down time, and the length of time in each period. In this analysis the length of each pumping period was set to conform to the critical irrigation periods for different crops in the region. Based on the initial input values for saturation thickness, pump lift, coefficient of storage, aquifer surface area, and the number of wells in the region, the maximum amount of water withdrawn by period is calculated. This figure is then used as a constraint for that particular iteration of the model. Given the very low recharge rate of the Ogallala aquifer, groundwater withdrawn for irrigation can be directly translated into a decline in saturation thickness and an increase in pump lift. At the start of each iteration of a temporal simulation, pump lift and saturation thickness values are adjusted to reflect current aquifer conditions which result from the summation of total water pumped in the previous periods. As more water is withdrawn from the aquifer, pump lift increases and well yield declines. The interaction of these factors increase the cost of irrigation in the region.

To compare the benefits over time of improving irrigation efficiency, a discounted present value formula is incorporated in the model. This formula discounts the stream of net returns above variable cost and net returns above total cost excluding payment for land, water, and management.

The discounted present value formula can be defined as:

$$PV = \sum_{t=1}^{T} \frac{NR_t}{(1+r)^t}$$

where PV is the present value, NR_t is net returns in year t, and r is the discount rate. Three discount rates of 2,4, and 6% were used to test the sensitivity of the various streams of net returns.

Regional Delineation

The High Plains study area was divided into two regions to reflect differences in resource availability and agronomic practices. The area to the north of the Canadian River is generally not suitable for cotton production and was designated as the Northern High Plains. By contrast, cotton production is a significant crop in the Southern High Plains. In addition, the spatial distribution of groundwater resources necessitates the division of the study area into two hydrologic units to represent differences in saturation thickness and pump lift within each subregion. Table 2 lists the initial weighted average values for saturation thickness and pump lift as well as cropland acres, wells, and contributing aquifer acres for both the Southern and Northern regions. After establishing the acreage which corresponds to different levels of groundwater, the cropland was divided into two classes based on low and high groundwater availability for each region.

Table 2. Intial Resource Condition: Texas High Plains

Water Situation	Wells	Contributing Aquifer Acres	Cropland Acres	Saturated Thickness	Pump Lift
		(1000)	(1000)	(ft)	(ft)
Northern Region					
Low	513.	471.	263.	77.	82.
High	8740.	5209.	2671.	207.	284.
Total	9253.	5680.	2934.		
Actual(1979)	8890.	5765.	2623.		
Southern Region					
Low	28988.	4630.	3630.	55.	145.
High	34616.	4872.	3550.	139.	281.
Total	63604.	9502.	7180.		
Actual(1979)	64460.	9340.	7183.		

Source: Reneau (1983).

Irrigation Distribution Systems

The development of more efficient irrigation distribution systems represents a form of improved technology. A distribution system that applies a greater proportion of total water pumped to the root zone would reduce the total quantity of water required for irrigation. A recent study of the High Plains and Winter Garden areas of Texas estimated the average distribution efficiency of center-pivot sprinkler systems at 61 percent and furrow irrigation systems at 60 percent (Texas Department of

Water Resources, 1983).

The first irrigation system to be considered is furrow irrigation. Furrow irrigation application efficiencies in the High Plains region range from 30 to 90 percent. There exists a number of techniques to improve the distribution efficiency of furrow systems. The major goal of these improved techniques is to provide a more uniform application of water to the plant thereby reducing deep percolation losses and surface evaporation. One method of improving furrow efficiency is to shorten row length. A study by Petty, Lacewell, Hardin, and Whitson (1980) indicated that a significant economic benefit could be realized by the more efficient application of irrigation water through utilization of shorter rows. These gains could be achieved with minimal cost and risk to the owner/operator. Additional techniques which can increase the application efficiency of furrow systems include the use of tailwater pits, alternate surge irrigation, and improved management procedures. With furrow irrigation systems, factors such as soil moisture intake rates, length of field, field slope, well capacity, weather, and management skills make the precise control of water application difficult. However, increases in furrow efficiency can be achieved at a relatively low expense.

The second major type of irrigation system to consider is center-pivot sprinklers. The application efficiency of these systems in the region range from 30 to 90 percent. Although sprinkler systems provide greater control over application rates as compared to furrow systems, this control is gained at the additional energy expense necessary to deliver water under greater pressure. Climatic conditions also influence the efficiency of sprinkler systems. High wind velocities can reduce sprinkler efficiency through water loss due to spray and surface evaporation. Like the furrow system, there are techniques which can improve the application efficiency of center-pivot systems. Two relatively inexpensive techniques include replacing nozzles and avoiding irrigation on very windy days.

A third irrigation system considered is the low energy precise application system or LEPA. Rather than spray the water into the air at high pressures, the LEPA system distributes the water directly into the furrow at a low pressure through drop tubes and controlled emitters. The LEPA system is used in conjunction with micro-basin land preparation techniques to maximize the utilization of scarce rainfall. The use of micro-basin techniques is essential to maintain the high application efficiency associated with the LEPA system. The application efficiency of the LEPA system has been measured at 92 to 96% efficiency in actual field trials.

Although the development of low pressure distribution systems could reduce irrigation fuel requirements, the inital investment and the degree of water and fuel saving will ultimately determine the economic feasibility of these types of systems. Given the large number of alternative techniques available to increase the application efficiency of irrigation systems, it is not clear which technique or combination of techniques will be the most economical from the producers standpoint.

Procedures

To evaluate the benefits of improving irrigation efficiency, the recursive programming model was applied to a 160 acre land relating to furrow irrigation and a 160 acre land unit relating to sprinkler irrigation for both the Northern and Southern High Plains. Each land unit represents the average soil types and agronomic characteristics found in each water resource situation. The water resource situations are the initial saturation thickness and pump lift given in Table 2. To asssess the benefits of improving irrigation efficiency, four discrete efficiency levels were evaluated for both furrow and center-pivot systems. The discrete distribution efficiencies considered were 50,60,70 and 80%. An additional 92% efficiency was evaluated to estimate the benefits of the LEPA system. Each level of distribution efficiency was simulated over a twenty year time horizon to reflect the impact of declining groundwater on the benefits from improving irrigation efficiency. To test the sensitivity of input and output prices on the stream of net returns, a low and average price scenario was simulated for each level of efficiency.

The economic benefit of improving irrigation efficiency was estimated by taking the difference in the present value of the stream of benefits above variable cost evaluated over the twenty year horizon at a 6% discount rate. It should be noted that the relative magnitude of benefits from improving irrigation efficiency will depend on the current system in use and its efficiency, the expected price of inputs and outputs, the discount rate, and the initial groundwater situation. Also, again the reader is reminded that the cost of achieving an improvement in distribution efficiency from X% to Y% is not included in the analysis.

RESULTS

The value of benefits listed in this analysis are the maximum that an owner/operator could afford to pay to improve irrigation efficiency on a representative 160 acre land unit. If the cost associated with improving irrigation efficiency is less than the benefits, then the adoption of improved irrigation techniques will be profitable. The actual cost of improving irrigation efficiency will vary depending on input and output prices, interest rates, soil type, topography, etc. The cost of improving the application efficiency of furrow and sprinkler irrigation systems is difficult to determine based on the wide variation in influential factors. However, it is important to at least determine the cost magnitude associated with each of the improved irrigation techniques.

The expected cost of improving the application efficiency of a furrow system typically is relatively low. Substantial improvements in the application efficiency of furrow systems can be achieved by improving management techniques. By contrast, the cost of implementing a furrow surge irrigation system for 160 acres is approximately $3,660 (Board,1984). The estimated cost of improving the application efficiency of center-pivot systems range from $3000 to $5000.

In addition to the cost of improving the application efficiency of a current system, it is also necessary to consider the transitional cost of changing systems. Lacewell and Collins (1983) estimated the transition cost from a furrow system to a center-pivot system at $35,000 to $40,000 on a 160 acre land unit. They also estimated the cost of retrofitting a center-pivot sprinkler system to the LEPA system at $8,000. It should be noted again that the previous cost estimates are only approximations to the actual cost. The actual cost of improving irrigation application efficiency will depend on numerous factors which are beyond the scope of this analysis.

The following section presents the results of the recursive programming model simulations for the Northern and Southern Texas High Plains. Each region was modeled for two crop price levels, two initial groundwater situations, and various distribution efficiencies for furrow and sprinkler irrigation systems.

Southern High Plains

The first case evaluated in the Southern High Plains was assessing the economic benefit of improving irrigation efficiency with good groundwater availability and average commodity prices. Good groundwater availability corresponds to a saturation thickness of 139 feet and pump lift of 281 feet. The average commodity prices utilized in this simulation are listed in Table 2. In addition, this case will be used as a baseline to compare alternative simulations. Table 3 lists the present value of benefits of improving irrigation efficiency for furrow and sprinkler systems.

If an owner/operator's initial furrow efficiency is 50%, the present value of benefits for improving furrow irrigation efficiency to 80% would be $83,600 for a 160 acre land unit. The values list in Table 3 are the present value of benefits which do not include the initial cost of implementing an improved efficiency technique. Similarly, the present value of improving sprinkler irrigation efficiency from 50% to 80% is $89,700. It should be noted that both sprinkler and furrow irrigation

Table 3. Estimated Farmer Benefits of Improving Irrigation Efficiency: Southern High Plains[a]

FURROW

Current Efficiency	Improved Efficiency 60%	70%	80%
50%	30.7	60.7	83.6
60%	0.	30.0	52.9
70%		0.	22.9

SPRINKLER

Current Efficiency	Improved Efficiency 60%	70%	80%	92%[b]
50%	30.7	60.8	89.7	136.6
60%	0.	30.1	59.0	105.9
70%		0.	28.9	75.8
80%			0.	46.9

FURROW TO SPRINKLER

Furrow Efficiency	Sprinkler Efficiency 60%	70%	80%	92%
50%	10.3	40.4	69.3	116.2
60%	0.	9.7	38.6	85.5
70%		0.	8.6	55.5
80%			0.	32.6

[a] Assuming 160 acres with saturated thickness of 139 feet and lift of 281 feet under average crop prices calculated at a 6% discount rate over 20 years. The benefits listed are in $1,000 units and do not include the investment cost of improving efficiency.

[b] The 92% efficiency refers to the LEPA system while all other sprinkler is center-pivot.

systems exhibit diminishing marginal benefits of improving irrigation distribution efficiency. In conjunction with improving sprinkler irrigation efficiency, a series of 92% efficiency were utilized to simulate the benefits of the LEPA system. The discounted present value of improving sprinkler irrigation efficiency from 50% to 92% (LEPA) is $136,600.

The final method of improving irrigation efficiency considered under good groundwater availability and average prices is the transition from furrow irrigation to sprinkler irrigation. Given an initial furrow efficiency of 50%, the present value of benefits of attaining 80% sprinkler efficiency is $69,300. Similarly, the present value from 50% furrow efficiency to 92% LEPA efficiency is $116,200.

Listed in Table 4 are the discounted present value of benefits minus the estimated cost for improving irrigation efficiency under furrow, sprinkler, and furrow to sprinkler systems. Considering the estimated cost of retrofiting a center-pivot system to LEPA, the present value of benefits minus estimated cost for 50% efficiency to 92% efficiency (LEPA) would be $128,600. Considering the initial transition cost from furrow to sprinkler, the present value of benefits minus estimated cost from 50% to 80% efficiency would be $31,800 and $78,700 from 50% to 92% LEPA. Based upon the series of simulations under good groundwater availability and average commodity prices in the Southern High Plains, the results indicate it is more economical to improve the application efficiency of the current system in place than switch from furrow to a sprinkler or LEPA system.

The second case evaluted in the Southern High Plains was to determine the price sensitivity of improving irrigation application

Table 4. Estimated Cost Adjusted Farmer Benefits of Improving Irrigation Efficiency: Southern High Plains[a]

FURROW [b]

Current Efficiency	Improved Efficiency 60%	70%	80%
50%	28.9	58.9	81.8
60%	0.	28.2	51.1
70%		0.	21.1

SPRINKLER [c]

Current Efficiency	Improved Efficiency 60%	70%	80%	92%[d]
50%	26.7	56.8	85.7	128.6
60%	0.	26.1	55.0	98.9
70%		0.	24.9	67.8
80%			0.	38.9

FURROW TO SPRINKLER [e]

Furrow Efficiency	Sprinkler Efficiency 60%	70%	80%	92%
50%	-27.2	2.9	31.8	78.7
60%	0.	-27.8	1.1	48.0
70%		0.	-28.9	18.0
80%			0.	-4.9

[a] Assumes the same land area,price,and groundwater situation as in Table 3.

[b] Assumes an average cost of improved furrow irrigation of $1,800.

[c] Assumes an average cost of improving center-pivot irrigation of $4,000 and $8,000 for the LEPA system.

[d] The 92% efficiency corresponds to the LEPA system.

[e] Assumes an average transition cost from furrow to sprinkler irrigation of $37,500.

efficiency. The low commodity prices utilized in this series are listed as the alternative prices in Table 2.

From an initial furrow efficiency of 50% to an improved efficiency of 80%, the present value of benefits were estimated at $51,600. This figure in Table 5 represents a 38% decline in benefits as compared to the average crop price series. To improve sprinkler efficiency from 50% to 80%, the present value of benefits were estimated at $21,700. This is 75% less than the benefits estimated with average crop prices. Similarly, the stream of benefits were only $33,200 for going from the 50% sprinkler efficiency to the LEPA system. A more dramatic reduction in the present value of benefits from improved application efficiency using low crop prices as compared to average crop prices was predicted for the transition from furrow irrigation to sprinkler irrigation and LEPA. The transition from 50% furrow efficiency to 80% sprinkler efficiency gave a negative present value of benefits of $7,500 excluding the initial cost of changing systems. Similarly, the present value of benefits were only to $4,000 for the transition from 50% furrow irrigation to the 92% LEPA system. This is due to the very narrow profit margins at low crop prices and increased fuel use of sprinkler for the higher pressure requirements more than offset any advantages of improved distribution efficiency. This has serious implications for the adoption of new technology during periods of depressed prices.

Based on this series of simulations, it becomes evident that the introduction of low commodity prices further reduces the incentive to improve irrigation efficiency by changing from furrow to sprinkler systems. This result reinforces the earlier baseline simulation that it

Table 5. Estimated Farmer Benefits of Improving Irrigation Efficiency By and Among Systems: Southern High Plains[a]

FURROW

Current Efficiency	Improved Efficiency 60%	70%	80%
50%	21.1	39.6	51.6
60%	0.	18.5	30.5
70%		0.	12.0

SPRINKLER

Current Efficiency	Improved Efficiency 60%	70%	80%	92%[b]
50%	9.1	16.2	21.7	33.2
60%	0.	7.1	12.6	24.1
70%		0.	5.5	17.0
80%			0.	11.5

FURROW TO SPRINKLER

Furrow Efficiency	Sprinkler Efficiency 60%	70%	80%	92%[b]
50%	-20.1	-13.0	-7.5	4.0
60%	0.	-34.1	-28.6	-17.1
70%		0.	-47.1	-35.6
80%			0.	-47.6

[a] Assuming 160 acres with saturated thickness of 139 feet and lift of 281 feet under low crop prices calculated at a 6% discount rate over 20 years. The benefits listed are in $1,000 units and do not include the investment cost of improving efficiency.

[b] The 92% efficiency refers to the LEPA system while all other sprinkler is center-pivot.

is more economical to improve the application efficiency of the current system in use. Finally, the results of this series indicate that the present value of benefits from improved sprinkler efficiency and the LEPA irrigation system are more sensitive to low commodity prices relative to the furrow irrigation system.

The third case evaluted in the Southern High Plains was to determine the present value of benefits from improving irrigation application efficiency under poor groundwater availability and average commodity prices. The poor groundwater availability scenario applied in this series of simulations corresponds to a saturation thickness of 55 feet and an average pump lift of 145 feet. This series was evaluated to determine the sensitivity of the stream of benefits accruing from improved application efficiency under an alternative groundwater availability condition.

The present value of benefits for improving furrow irrigation efficiency in this case is listed in Figure B-1 in Appendix B. The present value of benefits for improving furrow efficiency from 50% to 80% was estimated at $40,200. This translates to a 52% decline in benefits as compared to the good groundwater, average price scenario. The present value of benefits for improving sprinkler efficiency and the LEPA system are presented in Figure B-2. In the example of improving sprinkler efficiency from 50% to 80%, the present value of benefits were estimated at $43,000. This also represents a 52% reduction in the value of benefits as compared to the baseline. The present value of benefits for improving sprinkler efficiency from 50% to 92% LEPA was estimated at $43,000 which corresponds to a 51% decline in benefits from the baseline.

The final means evaluated to improve irrigation efficiency under average commodity prices and poor groundwater availability is the transition from furrow irrigation to sprinkler irrigation. Figure B-3 contains the present value of benefits of changing systems for various application efficiency rates. In the simulation from 50% furrow efficiency to 80% sprinkler efficiency, the value of benefits was estimated to be $33,600 (a 51% decline compared to average crop prices and good groundwater). Similarly, the benefits of changing from 50% furrow to 92% LEPA were $66,900 or 50% lower than the baseline.

The results from this series of simulations indicate that the low initial groundwater situation consistently reduces the stream of benefits for improving irrigation efficiency by approximately 50% as compared to the baseline condition of good groundwater availability. Unlike the low price scenario, the low groundwater condition reduces the benefits of improving irrigation appliation efficiency across all distribution systems.

The final case evaluated in the Southern High Plains was to assess the benefits of improving irrigation efficiency under poor groundwater availability and low commodity prices. Given the results of the two previous cases, the rational for this series of simulations is to determine the combined magnitude of low groundwater availability and low crop prices on the present value of benefits from improved irrigation efficiency.

The present value of benefits of improved furrow irrigation efficiency is listed in Figure B-4. In the example of improving furrow efficiency from 50% to 80% the stream of benefits were $7,700 which relates to a 90% reduction in benefits as compared to the good groundwater, average price scenario. Figure B-5 presents the present value of benefits of improving the application efficiency of sprinkler irrigation systems. In the simulation of improving sprinkler efficiency from 50% to 80%, the value of benefits were $8,600 or 90% less than the baseline. Similiarly lower benefits were obtained in the case of improving sprinkler efficiency from 50% to 92% LEPA as compared to the baseline.

In the transition from furrow to sprinkler irrigation, the stream of benefits for different levels of application efficiencies are listed in Figure B-6. In the example of improving efficiency from 50% furrow to 80% sprinkler, the present value of benefits was an estimated $5,700, 92% less than the benefits estimated for the baseline. Similiar results were obtained for improving irrigation efficiency from 50% furrow to 92% LEPA.

Based on the results derived from the four series of simulations in the Southern High Plains, the present value of benefits derived from improved irrigation efficiency are highly sensitive to changes in commodity prices and initial groundwater levels. The price sensitivity simulations indicate that the center-pivot sprinkler and the LEPA irrigation systems are more sensitive to input and commodity prices as compared to the furrow irrigation systems. In addition, a low initial groundwater level will reduce the value of benefits from improved application efficiency across all systems.

Northern High Plains

The baseline case evaluated in the Northern High Plains simulated the economic benefit from improving irrigation efficiency with good groundwater availability and average crop prices. Good groundwater availability for the Northern High Plains corresponds to a saturation thickness of 207 feet and an average pump lift of 284 feet. The purpose of this series of simulations was to establish a baseline for comparison of the present value of benefits from improved irrigation application efficiency.

For furrow irrigation techniques under this scenario, the present value of benefits from improving irrigation efficiency from 50% to 80% were estimated at $78,000 on a 160 acre land unit. The estimated present value of benefits from improving sprinkler efficiency from 50% to 80% was $95,800. Table 6 presents the discounted present value of benefits from improving irrigation efficiency for various irrigation systems and different levels of initial and attained efficiency. In the case of improving sprinkler efficiency from 50% to 92% LEPA, the present value of benefits were estimated at $145,400.

The final means of improving irrigation efficiency investigated in the baseline case was the estimation of benefits derived from changing to a sprinkler or LEPA system from a furrow irrigation system. In the example of changing from 50% furrow to 80% sprinkler, the present value of benefits were estimated at $63,100.

Table 7 lists the cost adjusted value of benefits from improving irrigation efficiency for various systems. By accounting for the initial cost of retrofiting a sprinkler system to LEPA, the present value of benefits from 50% to 92% LEPA would be $137,400. Similiarly, if the benefits of going from furrow to LEPA are adjusted for the cost of transition, the present value of benefits would be $75,200.

Based on the results from this series of simulations for the Northern

Table 6. Estimated Farmer Benefits of Improving Irrigation Efficiency: Northern High Plains[a]

FURROW

Current Efficiency	Improved Efficiency 60%	70%	80%
50%	30.4	59.5	78.0
60%	0.	29.1	47.6
70%		0.	18.5

SPRINKLER

Current Efficiency	Improved Efficiency 60%	70%	80%	92%[b]
50%	39.5	68.8	95.8	145.4
60%	0.	29.3	56.3	105.9
70%		0.	27.0	76.6
80%			0.	49.6

FURROW TO SPRINKLER

Furrow Efficiency	Sprinkler Efficiency 60%	70%	80%	92%[b]
50%	6.8	36.1	63.1	112.7
60%	0.	5.7	32.7	82.3
70%		0.	3.6	53.2
80%			0.	34.7

[a] Assuming 160 acres with saturated thickness of 207 feet and lift of 284 feet under average crop prices calculated at a 6% discount rate over 20 years. The benefits listed are in $1,000 units and do not include the investment cost of improving efficiency.

[b] The 92% efficiency refers to the LEPA system while all other sprinkler is center-pivot.

Table 7. Estimated Cost Adjusted Farmer Benefits of Improving Irrigation Efficiency: Northern High Plains[a]

FURROW [b]

Current Efficiency	Improved Efficiency 60%	70%	80%
50%	28.6	57.7	76.2
60%	0.	27.3	45.8
70%		0.	16.7

SPRINKLER [c]

Current Efficiency	Improved Efficiency 60%	70%	80%	92%[d]
50%	35.5	64.8	91.8	137.4
60%	0.	25.3	52.3	97.9
70%		0.	23.0	68.6
80%			0.	41.6

FURROW TO SPRINKLER [e]

Furrow Efficiency	Sprinkler Efficiency 60%	70%	80%	92%[d]
50%	-30.7	-1.4	25.6	75.2
60%	0.	-31.8	-4.8	44.8
70%		0.	-33.9	15.7
80%			0.	-2.8

[a] Assumes the same land area,price,and groundwater situation in Table 6.

[b] Assumes an average cost of improved furrow irrigation of $1,800.

[c] Assumes an average cost of improving center-pivot irrigation of $4,000 and $8,000 for the LEPA system.

[d] The 92% efficiency corresponds to the LEPA system.

[e] Assumes an average transition cost from furrow to sprinkler irrigation of $37,500.

High Plains under average commodity prices and good groundwater availability, it is more economical to improve the application efficiency of the current system in use as opposed to switching distribution systems. In addition, the investment to improve irrigation efficiency exhibits diminishing marginal benefits for higher levels of efficiency.

The second case evaluated in the Northern High Plains was to determine the present value of benefits from improving irrigation application efficiency for good groundwater availability and low commodity prices. This set of simulations was designed to test the sensitivity of benefits from improved irrigation efficiency to low commodity prices.

The present value of benefits derived from improving furrow irrigation efficiency from 50% to 80% was $32,200. This corresponds to a 59% decrease in benefits as compared to the baseline condition. The simulation of improving sprinkler efficiency from 50% to 80% indicates that the present value of benefits would be $9,900 or decline by 90% from the baseline. Similiarly, the present value of benefits from improving sprinkler efficiency from 50% to 92% LEPA would be $43,600 or 70% less than the baseline.

Table 8 presents the value of benefits for improving irrigation efficiency by and among systems under good groundwater availability and low commodity prices. The transition from 50% furrow efficiency to 80% sprinkler efficiency under the low price scenario indicates that the present value of benefits would be a negative $4,400. The present value of benefits from the transition from 50% furrow to 92% LEPA were estimated at $29,300. This figure also represents a 74% reduction in the value of benefits as compared to the baseline simulation.

Table 8. Estimated Farmer Benefits of Improving Irrigation Efficiency By and Among Systems: Northern High Plains[a]

FURROW

Current Efficiency	Improved Efficiency 60%	70%	80%
50%	11.5	27.8	32.2
60%	0.	16.3	20.7
70%		0.	4.4

SPRINKLER

Current Efficiency	Improved Efficiency 60%	70%	80%	92%[b]
50%	1.6	7.4	9.9	43.6
60%	0.	5.8	8.3	42.0
70%		0.	2.5	36.2
80%			0.	33.7

FURROW TO SPRINKLER

Furrow Efficiency	Sprinkler Efficiency 60%	70%	80%	92%[b]
50%	-12.7	-6.9	-4.4	29.3
60%	0.	-18.4	-15.9	17.8
70%		0.	-32.2	1.5
80%			0.	-2.9

[a] Assuming 160 acres with saturated thickness of 207 feet and lift of 284 feet under low crop prices calculated at a 6% discount rate over 20 years. The benefits listed are in $1,000 units and do not include the investment cost of improving efficiency.

[b] The 92% efficiency refers to the LEPA system while all other sprinkler is center-pivot.

The results of the low commodity price series of simulations for the Northern High Plains indicate that the present value of benefits from improving sprinkler irrigation efficiency are very sensitive to commodity price levels. The low commodity price level also reduces the benefits for furrow and LEPA irrigation systems, however, the furrow system appears to be the least sensitive to the low commodity price scenario.

The third case evaluated in the Northern High Plains was to determine the benefits of improving irrigation efficiency under average commodity prices and poor groundwater availability. The rational for this series of simultions was to assess the impact of a low initial groundwater situation on the stream of benefits from improving irrigation efficiency. The poor groundwater situation in this case relates to a saturation thickness of 77 feet and an average pump lift of 82 feet.

The present value of benefits for improving furrow irrigation efficiency from 50% to 80% is $21,900. This figure represents a 72% decrease in benefits as compared to the baseline with good groundwater availability. Figure B-7 displays the present value of benefits for improving furrow irrigation for various levels of initial efficiency. In the examples of improving sprinkler efficiency from 50% to 80% and 50% to 92% LEPA, the value of benefits were estimated at $24,000 and $38,100 respectively. In comparison to the baseline case, both examples represent a 75% reduction in the stream of benefits. Figure B-8 presents the estimated benefits from improving sprinker irrigation efficiency.

Figure B-9 lists the estimated benefits derived from changing from furrow irrigation to sprinkler irrigation. In the case of transition from furrow to sprinkler, the present value of benefits were reduced by 70% to

75% compared to the baseline of average crop prices and good groundwater. In the simulation of the transition from 50% furrow to 80% sprinkler efficiency, the present value of benefits were estimated at $18,200.

The final case analyzed for the Northern High Plains was to determine the benefits of improving irrigation efficiency under low commodity prices and a low initial groundwater level. The purpose of this series of simulations was to assess the interactive impact of these two conditions on the stream of benefits from improving irrigation efficiency.

The present value of benefits for improving furrow irrigation efficiency from 50% to 80% was estimated at $4,000. This represents a 95% reduction in benefit from the baseline scenario. Figure B-10 and B-11 illustrates the estimated benefits for improving furrow and sprinkler irrigation efficiency under the low price and groundwater case. Similarily, the stream of benefits from improving sprinkler efficiency from 50% to 80% were only $6,000 or 84% less than the baseline. The simulation of improving sprinkler efficiency from 50% to 92% LEPA gave a benefit of $18,000.

The evaluation of the benefits derived from the transition to sprinkler from furrow irrigation are displayed in Figure B-12. In the example of changing from 50% furrow efficiency to 92% LEPA, the present value of benefits were estimted at $14,900. This corresponds to an 87% decline in benefits as compared to the baseline case.

Based on the results from the four series of simulations for the Northern High Plains, it is apparent that the benefits derived from improving sprinkler efficiency are highly sensitive to low commodity price levels. This series of simulations support an earlier finding that it is more economical to improve the efficiency of the current irrigation system in place as opposed to changing from one system to another.

SUMMARY

From the results presented in the previous section, it is apparent that low crop prices significantly reduce the incentive to invest in more efficient irrigation equipment. This result is consistent for each region within the High Plains study area. In addition, the low crop price scenario for each region indicates a differential impact among various irrigation systems. In particular, the benefits from improving sprinkler efficiency were dramatically reduced in relation to the baseline under the low price sitution as compared to the reduction in benefits from improving furrow efficiency.

Although commodity price levels affect the present value of benefits from improved irrigation efficiency, a second factor which requires careful consideration is the initial groundwater situation. The results of this analysis indicate that a low initial groundwater level will consistently reduce the present value of benefits from improved efficiency across all irrigation systems. In addition, the initial groundwater situation must be evaluated in terms of the investment required to improve irrigation efficiency. Under a low groundwater level, there is less physical resource to recover the initial investment.

In the majority of cases evaluated, the benefits of improving irrigation efficiency by 20 to 30% are very large. However, the results of this study indicate that it is generally more economical to improve the efficiency of the current system in use than to change irrigation systems. In all cases considered, it is economically more attractive to obtain 80% efficiency on a furrow system in place rather than to purchase a LEPA system.

In conclusion, the results from this analysis indicate that substantial benefits can be gained by improving the application efficiency of the irrigation system already in place. Although there are numerous new techniques available to improve irrigation application efficiency, these techniques can be very expensive to implement and may not be an economical investment decision for a particular producer.

Limitation

Among the limitations of this study are:

(1) Labor implications of alternative systems which may favor the sprinkler or LEPA systems.

(2) Risk in crop prices, input prices, or crop yield.

(3) Influence of taxes such as investment credit on economic profitability.

(4) Role of lease-purchase agreements and their effect.

(5) Individual farmer preferences and aversion to risk.

(6) The integral facets of management involved in irrigated agriculture and sensitivity of economics to these factors.

Thus, these results provide useful guidelines in considering upgrading of a distribution system. However, knowledge of the current efficiency is critical. Also, this efficiency will vary across crops, fields, and seasons of the year. As in any investment decision, more knowledge is preferred to less. The intent of this report is to provide more information for decision making.

REFERENCES

Board, Wayne L., "Farmers Cite Surge Irrigation Advantages." Southwest Farm Press, February 2, 1984.

Frederick, Kenneth D. and James C. Hanson. *Water for Western Agriculture.* Resources for the Future, Washington, D.C.,1982.

Grubb, Herbert W. and Ronald D. Lacewell. *Economic Evaluation of Alternative Temporal Water Use Plans on Cotton-Sorghum Farms in the Fine-Textured Soils of the Texas High Plains.* Texas Agricultural Experiment Station, TR 70-3, May 1970.

Hardin, Daniel C. and Ronald D. Lacewell. *Break-Even Investment in a Wind Energy Conversion System for an Irrigated Farm on the Texas High Plains.* Texas Water Resources Institute, TR-116, October 1981.

Hardin, Daniel C. and Ronald D. Lacewell. *Break-even Natural Gas Prices for Irrigation: Texas High Plains.* Texas Agricultural Experiment Station, TA-13361, April,1977.

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.

Lacewell,Ronald D. and Glenn S. Collins. *Magnitude of a State Bond Financed, Low Interest Program to Aid Farmers in Purchasing More Efficient Irrigation Equipment.* Department of Agricultural Economics, Texas A&.M University, January 6, 1983.

Lacewell, Ronald D., Gary D. Condra, and Brian Fish. *Energy and Irrigation.* Presented at the Energy and Agricultural Symposium, Center for the Biology of Natural Systems, St. Louis, Missouri, June,1976.

Lacewell, Ronald D., Daniel Hardin, James Petty, and Robert Whitson. *Economic Effect of Energy Price and Economic Feasibility and Potential of New Technology and Improved Management for Irrigation in Texas.* Texas Water Resource Institute, TR-119, May,1982.

Lyle, William M. and James P. Bordovsky. *New Irrigation System Design for Maximizing Irrigation Efficiency and Increasing Rainfall Utilization.* Texas Water Resource Institute, TR-105, May 1980.

Lyle, W.M., J.P. Bordovsky, L. Vrubel, and D.C. Lorenz. *Evaluation of Low Energy, Precision Application Irrigation at the Texas Agricultural Experiment Station, Halfway, Texas.* Annual Progress Report, Texas Agricultural Experiment Station, 1981.

Muller, Daniel A. and Robert D. Price. *Groundwater Availability in Texas: Estimates and Projections Through 2030.* Texas Department of Water Resources, Report 238, September, 1979.

Petty, James A. *Impact of Alternative Energy Prices, Tenure Arrangements, and Irrigation Technologies on a Typical Texas High Plains Farm Firm.* Ph.D. Dissertation, Texas A&.M University, May,1980.

Petty, James A., Ronald D. Lacewell, Daniel C. Hardin, and Robert E. Whitson. *Impact of Alternative Energy Prices, Tenure Arrangements and Irrigation Technologies on a Typical Texas High Plains Farm.* Texas Water Resources Institute, TR-106, May, 1980.

Reneau, Duane R. *Technological Response to Natural Resource Depletion: A Model of Crop Agriculture on the Texas High Plains.* Ph.D. Dissertation, Texas A&.M University, December, 1983.

Reneau, Duane R., Ronald D. Lacewell, and John R. Ellis. *Impact of New Irrigation Technology on the Texas High Plains: 1980-2020.* Texas Water Resources Institute, TR-129, February,1984.

Skold, Melvin D. *Farmer Adjustments to Higher Energy Prices: The Case of Pump Irrigators.* U.S.D.A., Natural Resource Economics Division, E.R.S.-663, November, 1977.

Sloggett, Gordon. *Prospects for Groundwater Irrigation: Declining Levels and Rising Energy Costs.* U.S.D.A.,E.R.S., Agricultural Economic Report No. 478, 1981.

Reneau, Duane R., Ronald D. Lacewell, and John R. Ellis. *Recursive Programming Model For Crop Production on the Texas High Plains.* Texas Water Resources Institute, TR-129, February,1984.

Texas Crop and Livestock Reporting Service. *Texas Agricultural Cash Receipts, Prices Received and Paid by Farmers.* U.S. Department of Agriculture, Austin, Texas, 1962-1981.

Texas Department of Water Resources. *Inventories of Irrigation in Texas: 1958, 1964, 1969, 1974, and 1979.* Report 263, October,1981.

Texas Water Development Board. *Continuing Water Resources and Development for Texas.* Planning Series Report P34, May 1977.

Wyatt, A.W., A. Bell, and S. Morrison. *Analytical Study of the Ogallala Aquifer in Lamb County, Texas-Projections of Saturation Thickness, Volume of Water in Storage, Pumpage Rates, Pumping Lifts, and Well Yields.* Texas Water Development Board, Report 204, 1976.

Wyatt, Wayne. *High Plains Underground Water Conservation District No.1,* Unpublished Irrigation System Efficiency Evaluations, 1978-1981.

APPENDIX A

Table A-1. Production Inputs For Conventional and Reduced Tillage

Item	Unit	Cotton	Corn	Sorghum	Soybean	Wheat	Fallow
Conventional Tillage							
Irrigated							
Labor	hrs	6.13	4.61	5.35	4.55	3.10	
Seed	$	9.00	17.20	3.60	13.80	9.75	
Biocides	$		28.00	10.50	7.00	5.62	
Diesel	gal	14.63	12.76	20.62	12.85	8.74	
Machinery							
Variable	$	9.16	6.62	7.21	7.49	6.66	
Fixed	$	37.21	36.31	23.42	21.91	26.53	
Dryland[a]							
Labor	hrs	5.28		2.31		2.18	1.84
Seed	$	4.75		1.80		3.00	
Biocides	$	6.00					
Diesel	gal	14.15		9.47		8.19	5.10
Machinery							
Variable	$	6.74		4.16		3.58	3.19
Fixed	$	31.16		17.37		19.63	15.63
Reduced Tillage							
Irrigated							
Labor	hrs	4.64	2.73	3.72	2.83	1.88	
Seed	$	9.00	17.20	3.60	13.80	9.75	
Biocides	$	6.00	42.00	17.00	12.00	17.00	
Diesel	gal	10.70	9.65	14.22	8.86	6.03	
Machinery							
Variable	$	7.07	4.57	4.97	5.25	4.59	
Fixed	$	30.38	27.44	16.15	15.35	20.41	
Dryland							
Labor	hrs	2.92		1.39		1.32	1.07
Seed	$	6.75		1.80		3.00	
Biocide	$	6.00		6.00		4.00	7.50
Diesel	gal	8.53		5.69		5.65	2.34
Machinery							
Variable	$	2.92		1.39		1.32	1.07
Fixed	$	28.73		13.36		15.10	9.09

[a] Corn and soybeans are not raised in dryland conditions.

Source: Reneau, Lacewell, and Ellis (1983).

Table A-2. Yield Related Inputs: Fertilizer and Harvesting Equations

Crop	Crop Unit	Yield Level	Nitrogen	Phosphorus	Harvesting/ Hauling
			(lb)	(lb)	($)
Cotton	lb		.0533Y	.0533Y	5.5[a](.04Y)
Corn	bu	Y<100	1Y	.6Y	.6Y
		Y>100	100+.8(Y-100)	60.	
Sorghum	cwt	Y<40	1.5Y	1Y	.62Y
		40<Y<60	60+2(Y-40)	40.	
		Y>60	100+2(Y-60)	40+(Y-60)	
Soybeans	bu		20	.5Y	12.5+.10Y
Wheat	bu	Y<20			12+.12Y
		Y<40	1.5Y	.5Y	
		Y>20			14.4+.24(Y-20)
		Y>40	60+2(Y-40)	20+(Y-40)	

[a] Cotton harvest,gin,bag,and tie are based on seed cotton at 5.5 lbs. seed cotton per lb. lint.

Source: Reneau 1983

Table A-3. Irrigation Distribution Input Costs on a Per Acre-Inch Basis

Item	Unit	Furrow		Sprinkler	
		Standard	Improved	Standard	LEPA[a]
Annual Fixed Cost[b]	$	1.06	1.14	1.61	1.93
Annual Variable Cost[b]	$	.21	.27	.46	.59
Labor	hr	.10	.15	.033	.043
Pumping Head	psi	5	5	45	6
Delivery Efficiency	%	69	80	80	92

[a] LEPA is the Low Energy Precise Application irrigation system described by Lyle and Bordovsky (1980).

[b] Fixed and variable costs are for the distribution system only. Well, pump, and fuel costs are calculated separately.

Source: Reneau, Lacewell, and Ellis (1983).

APPENDIX B

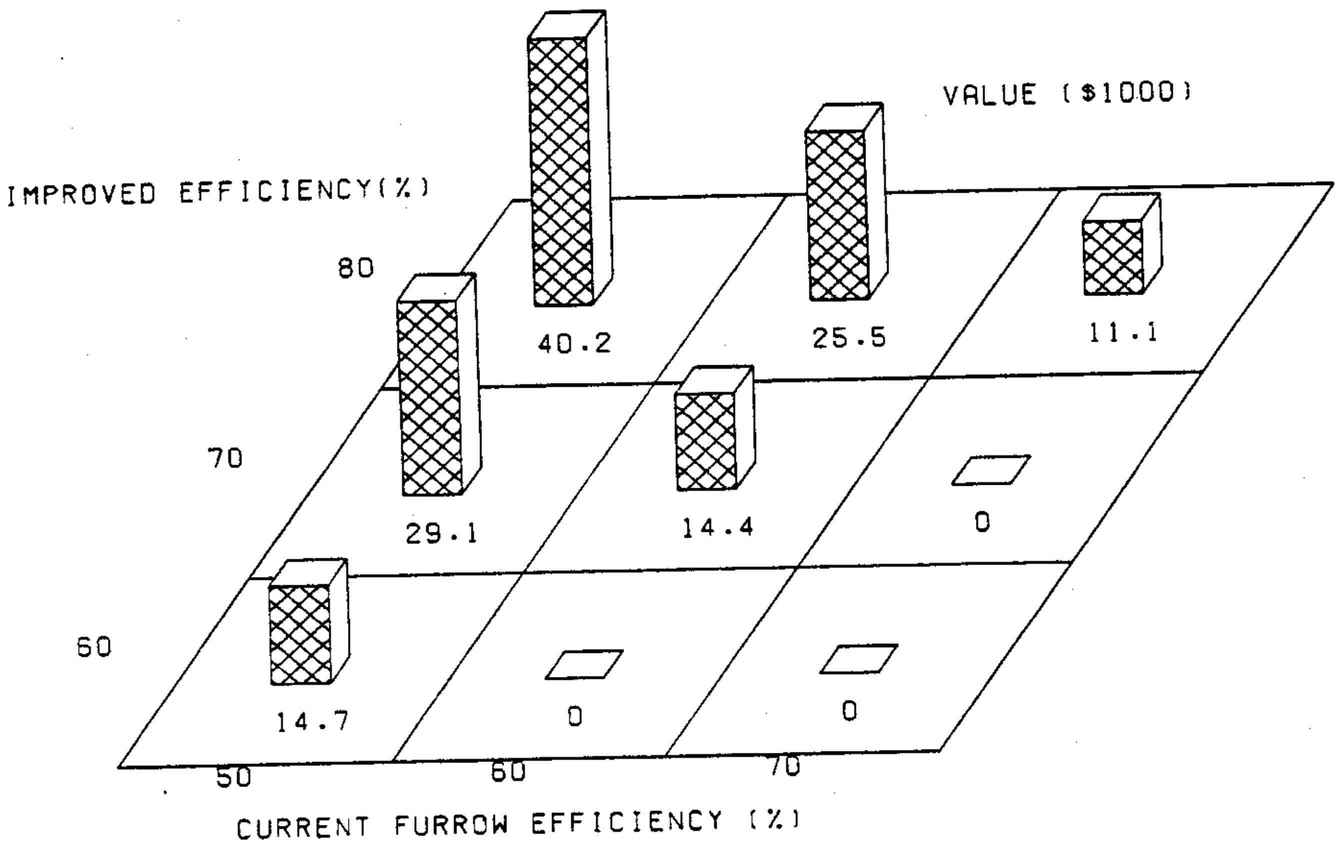

Figure B-1. Discounted Present Value for 160 Acres of Improved Furrow Efficiency: Southern High Plains.[a]

[a] Assumes an initial 55 ft. saturation thickness, 145 ft. lift, 6% discount rate over a 20 year planning horizon and average prices. The values listed are the maximum that could be expended to improve irrigation efficiency from X% to Y%.

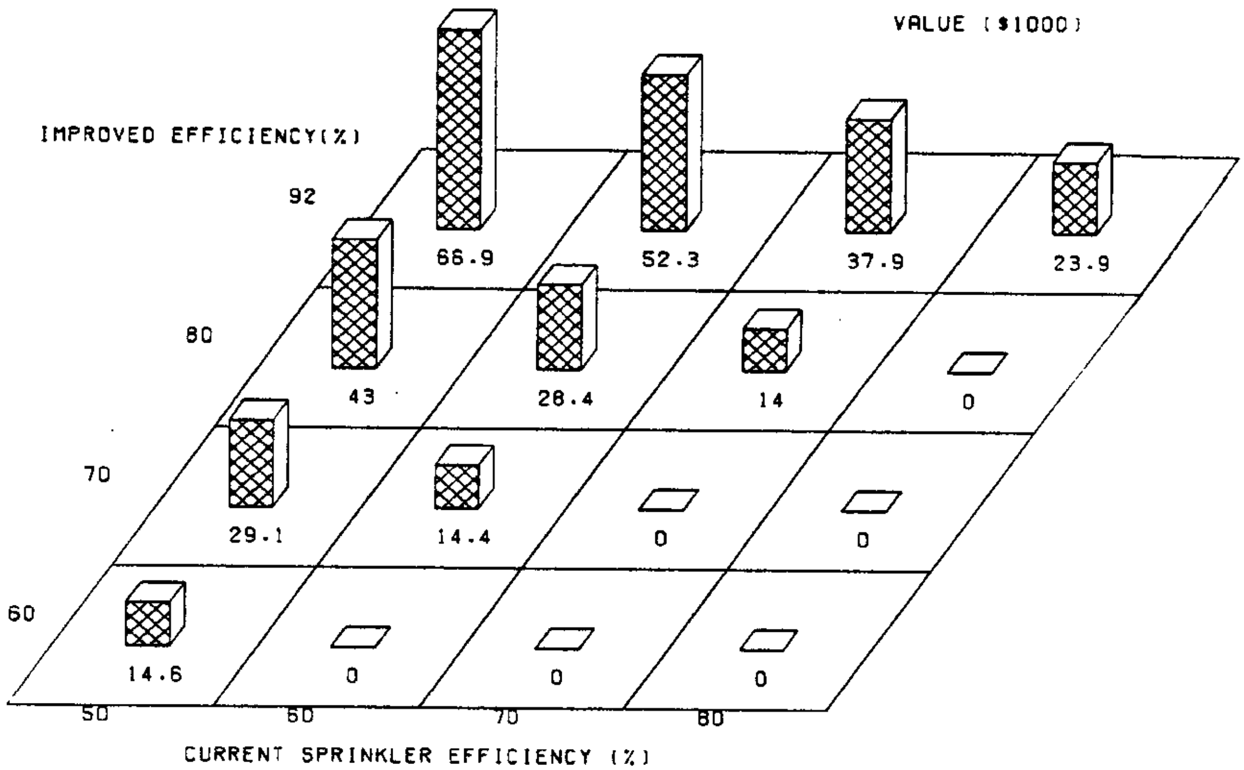

Figure B-2. Discounted Present Value for 160 Acres of Improved Sprinkler Efficiency: Southern High Plains.[a]

[a] Assumes an initial 55 ft. saturation thickness, 145 ft. lift, 6% discount rate over a 20 year planning horizon and average prices. The values listed are the maximum that could be expended to improve irrigation efficiency from X% to Y%.

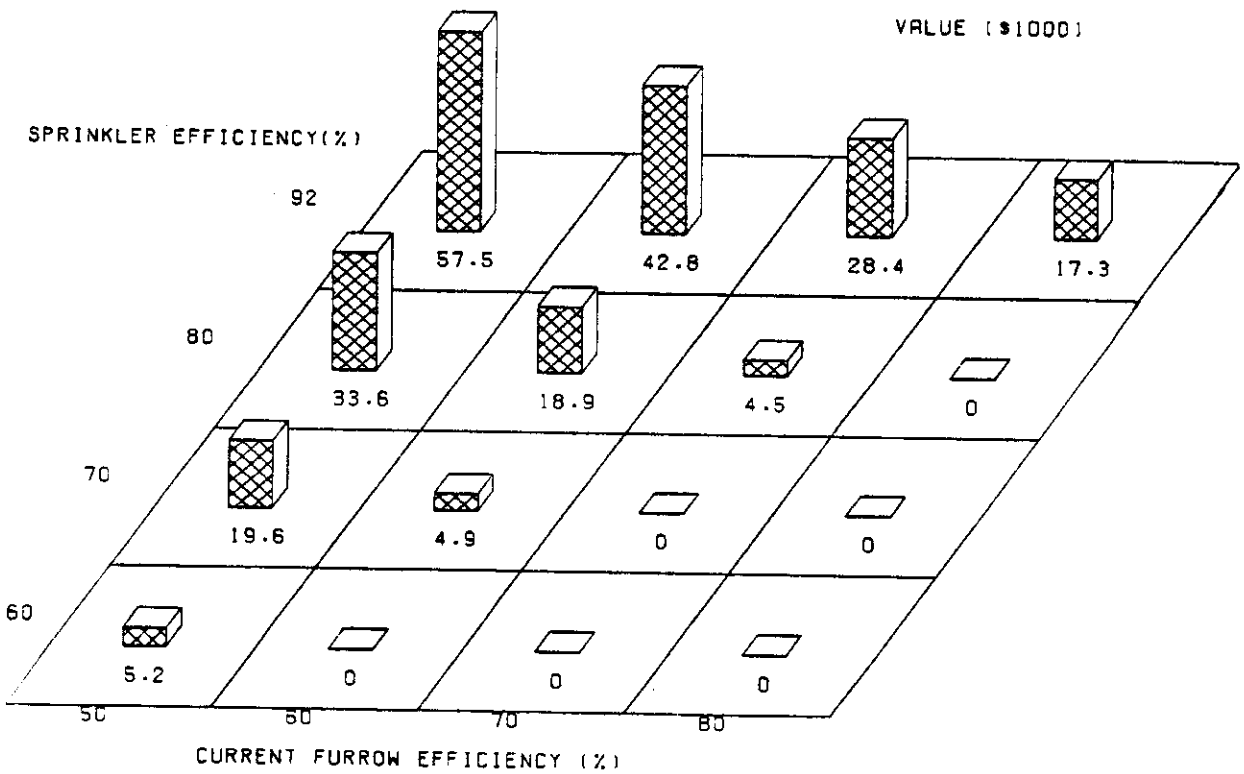

Figure B-3. Discounted Present Value for 160 Acres of Improved Irrigation Efficiency From Furrow to Sprinkler: Southern High Plains.[a]

[a] Assumes an initial 55 ft. saturation thickness, 145 ft. lift, 6% discount rate over a 20 year planning horizon and average prices. The values listed are the maximum that could be expended to improve irrigation efficiency from X% to Y%.

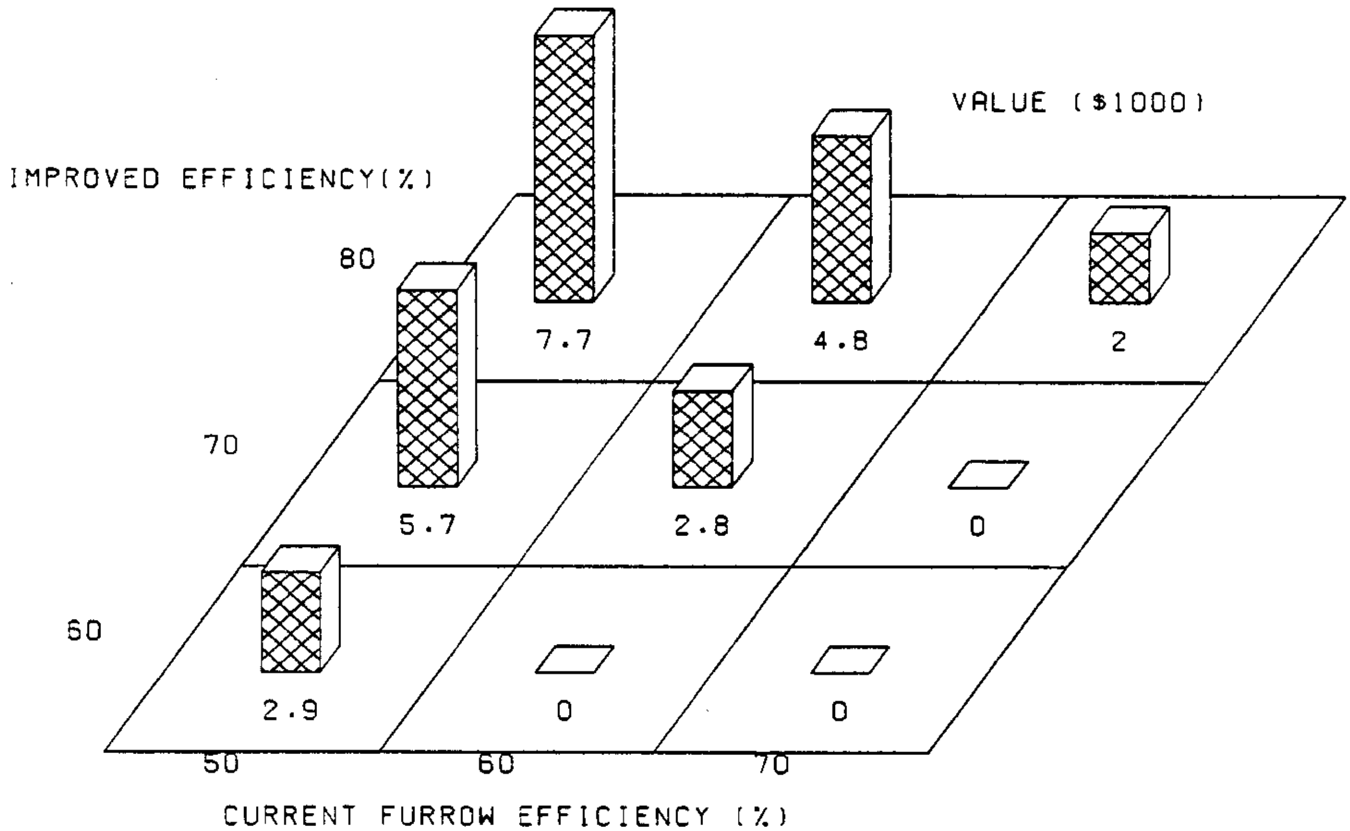

Figure B-4. Discounted Present Value for 160 Acres of Improved Furrow Efficiency: Southern High Plains.[a]

[a] Assumes an initial 55 ft. saturation thickness, 145 ft. lift, 6% discount rate over a 20 year planning horizon and low crop prices. The values listed are the maximum that could be expended to improve irrigation efficiency from X% to Y%.

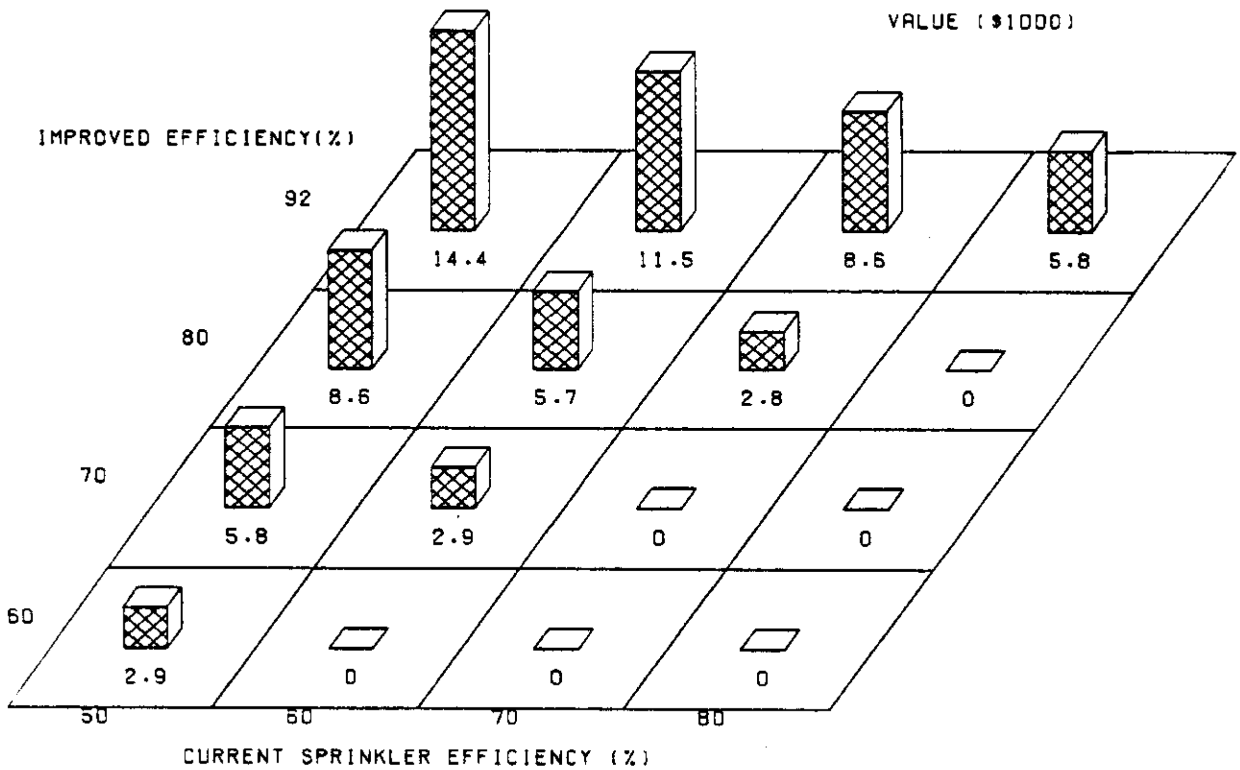

Figure B-5. Discounted Present Value for 160 Acres of Improved Sprinkler Efficiency: Southern High Plains.[a]

[a] Assumes an initial 55 ft. saturation thickness, 145 ft. lift, 6% discount rate over a 20 year planning horizon and low crop prices. The values listed are the maximum that could be expended to improve irrigation efficiency from X% to Y%.

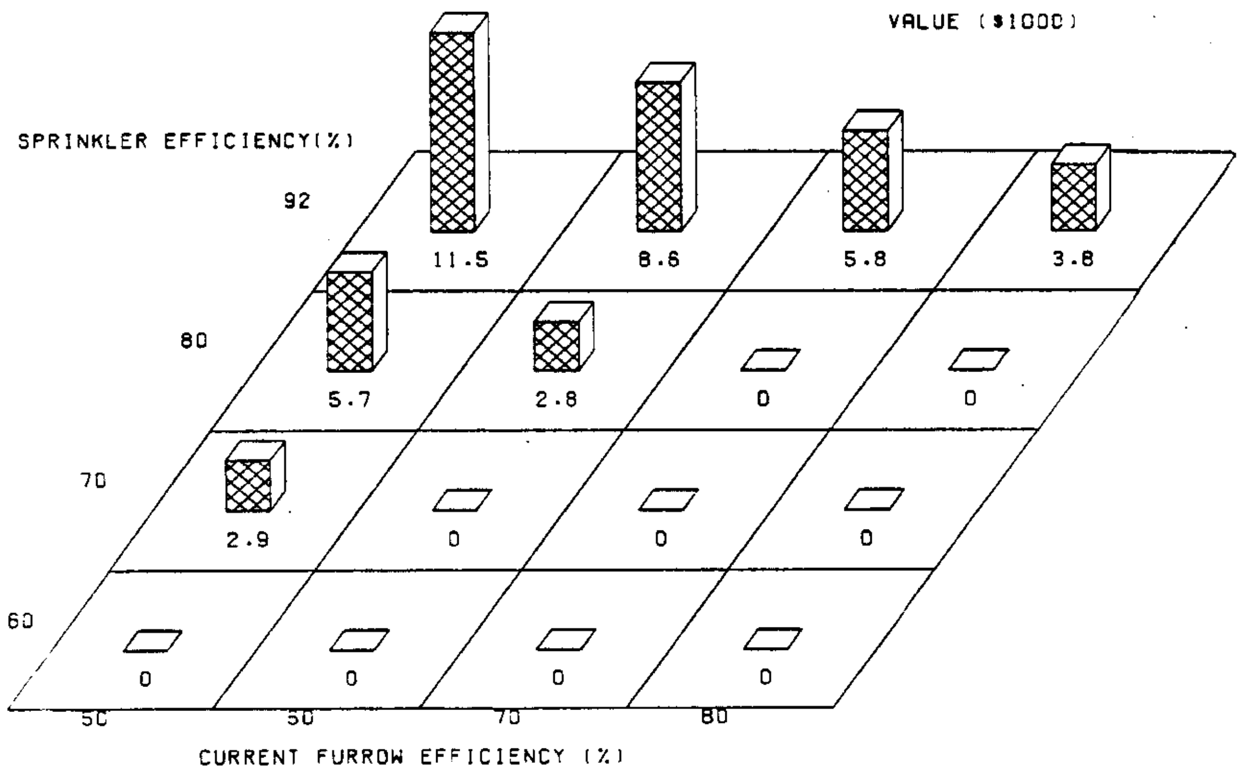

Figure B-6. Discounted Present Value for 160 Acres of Improved Irrigation Efficiency From Furrow to Sprinkler: Southern High Plains.[a]

[a] Assumes an initial 55 ft. saturation thickness, 145 ft. lift, 6% discount rate over a 20 year planning horizon and low crop prices. The values listed are maximum that could be expended to improve irrigation efficiency from X% to Y%.

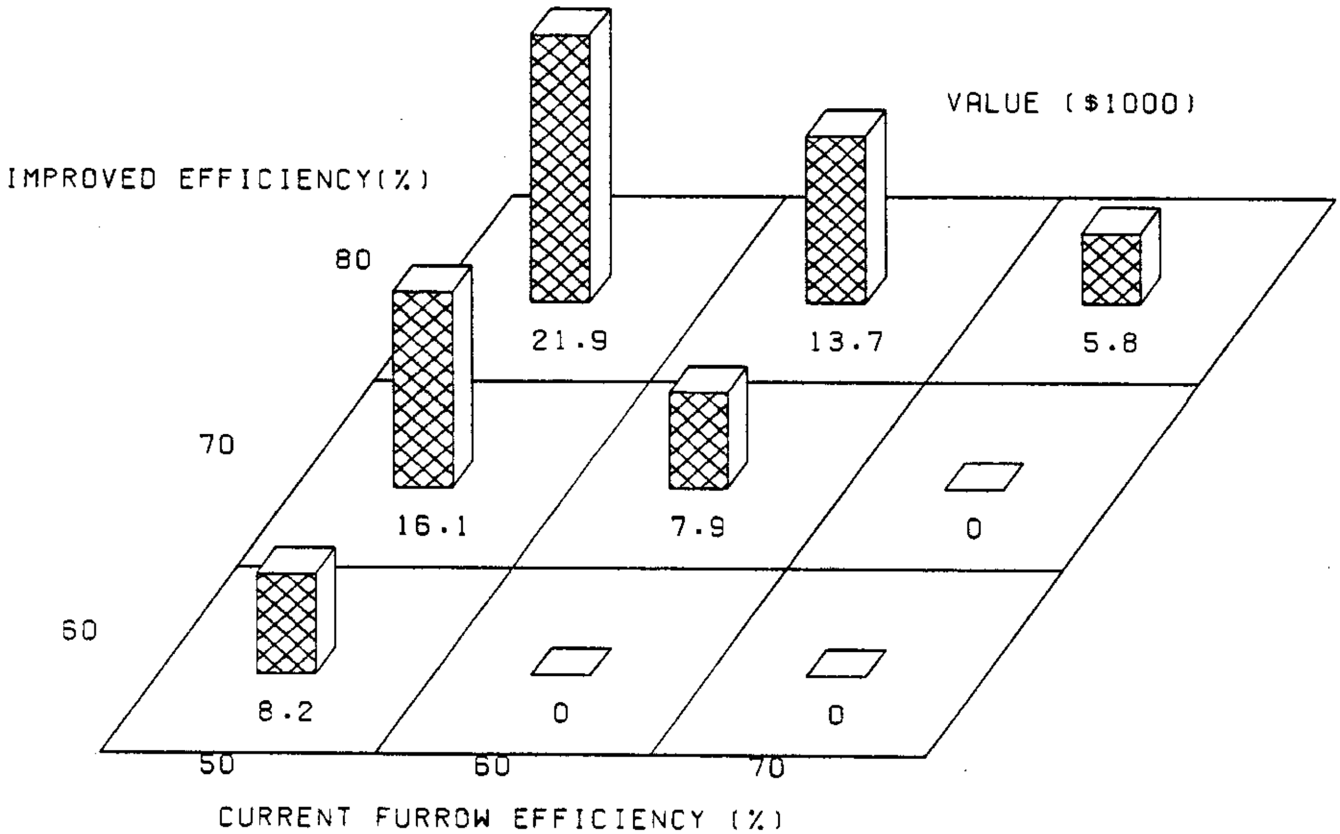

Figure B-7. Discounted Present Value for 160 Acres of Improved Furrow Efficiency: Northern High Plains.[a]

[a] Assumes an initial 77 ft. saturation thickness, 82 ft. lift, 6% discount rate over a 20 year planning horizon and average crop prices. The values listed are the maximum that could be expended to improve irrigation efficiency from X% to Y%.

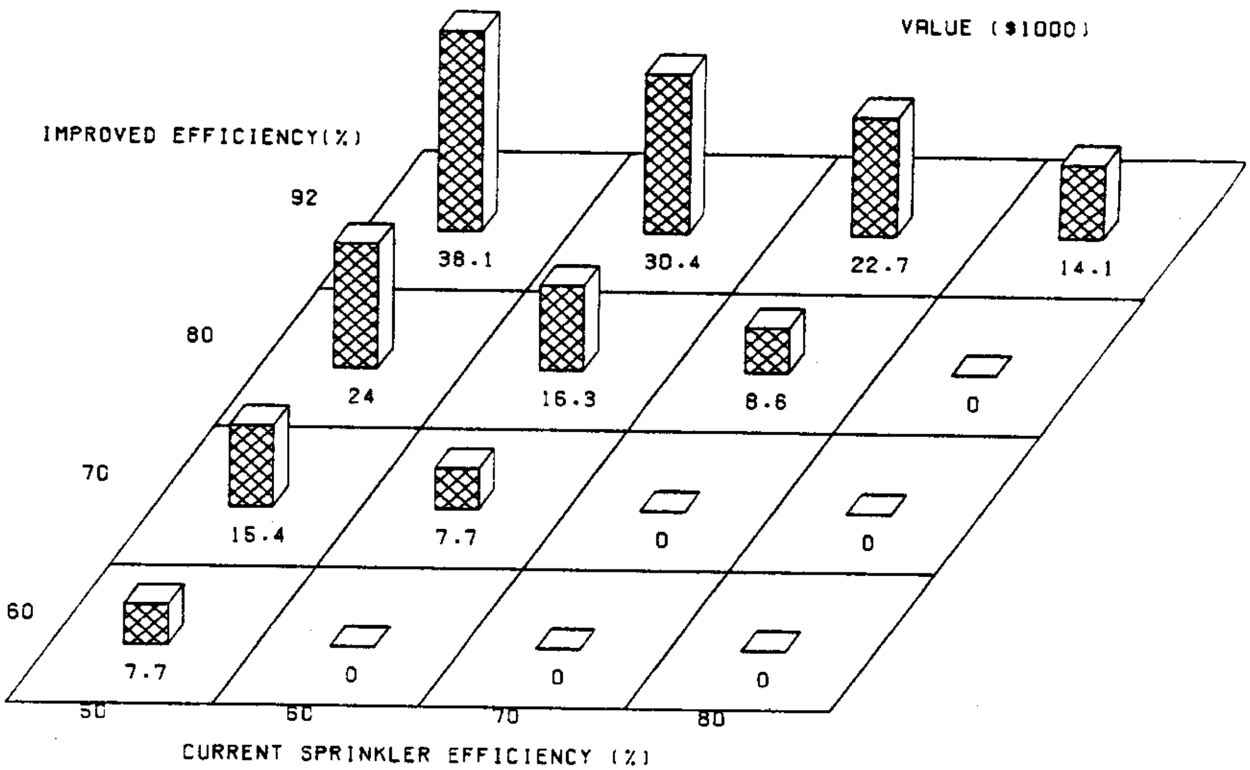

Figure B-8. Discounted Present Value for 160 Acres of Improved Sprinkler Efficiency: Northern High Plains.[a]

[a] Assumes an intial 77 ft. saturation thickness, 82 ft. lift, 6% discount rate over a 20 year planning horizon and average crop prices. The values listed are the maximum that could be expended to improve irrigation efficiency from X% to Y%.

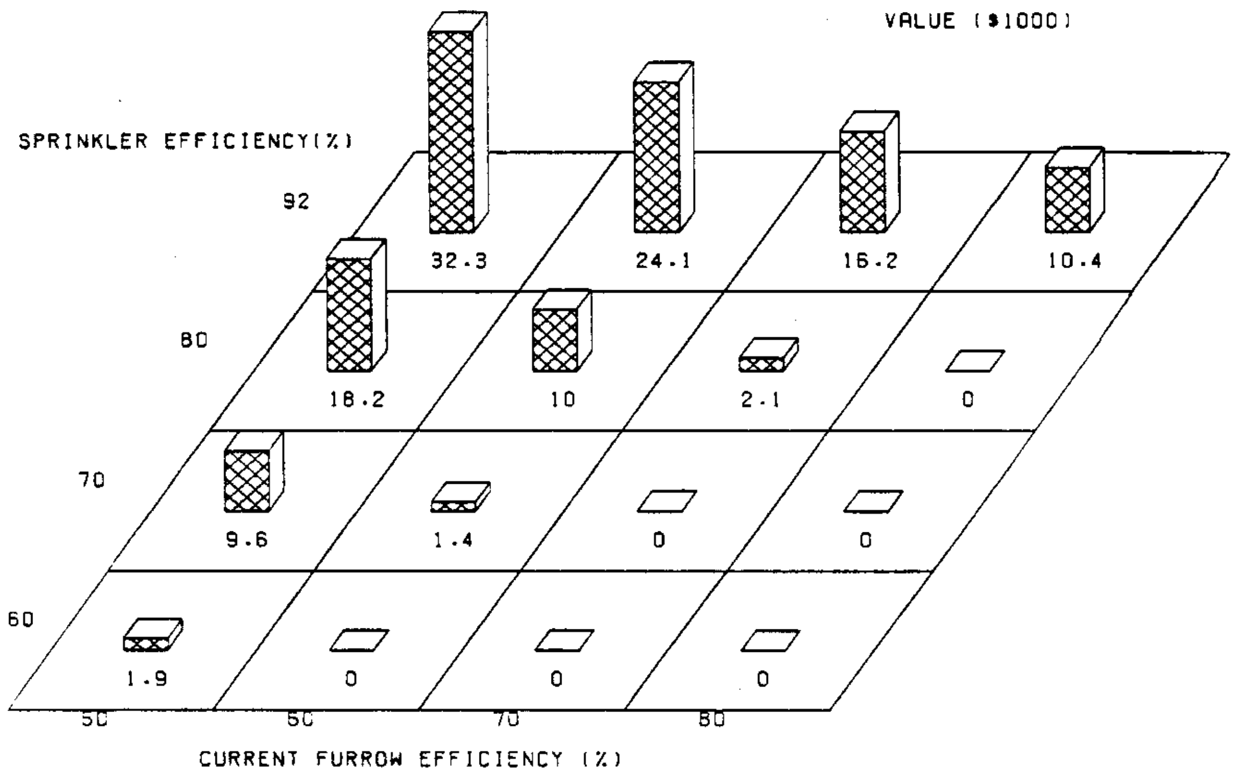

Figure B-9. Discounted Present Value for 160 Acres of Improved Irrigation Efficiency From Furrow to Sprinkler: Northern High Plains.[a]

[a] Assumes an initial 77 ft. saturation thickness, 82 ft. lift, 6% discount rate over a 20 year planning horizon and average crop prices. The values listed are the maximum that could be expended to improve irrigation efficiency from X% to Y%.

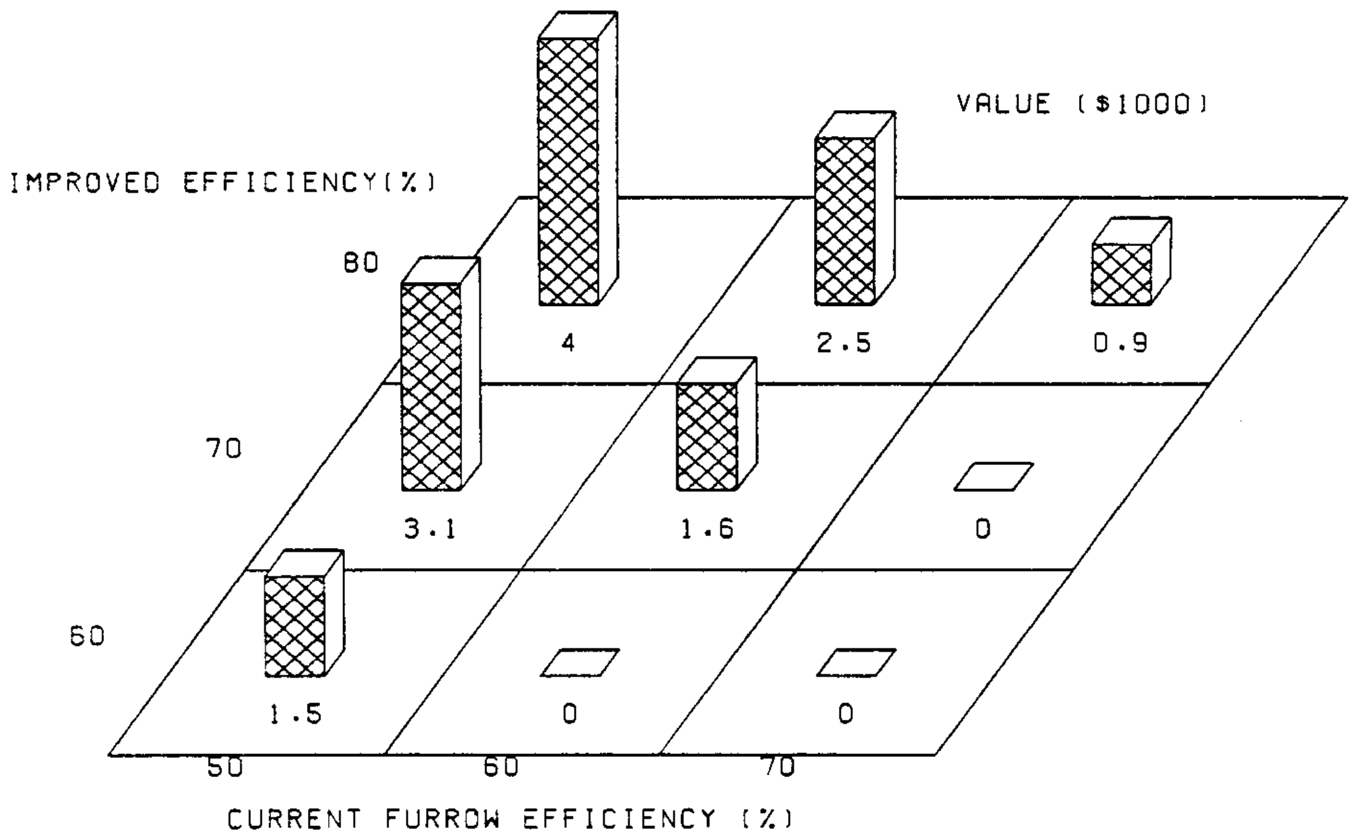

Figure B-10. Discounted Present Value for 160 Acres of Improved Furrow Efficiency: Northern High Plains.[a]

[a] Assumes an initial 77 ft. saturation thickness, 82 ft. lift, 6% discount rate over a 20 year planning horizon and low crop prices. The values listed are the maximum that could be expended to improve furrow irrigation efficiency from X% to Y%.

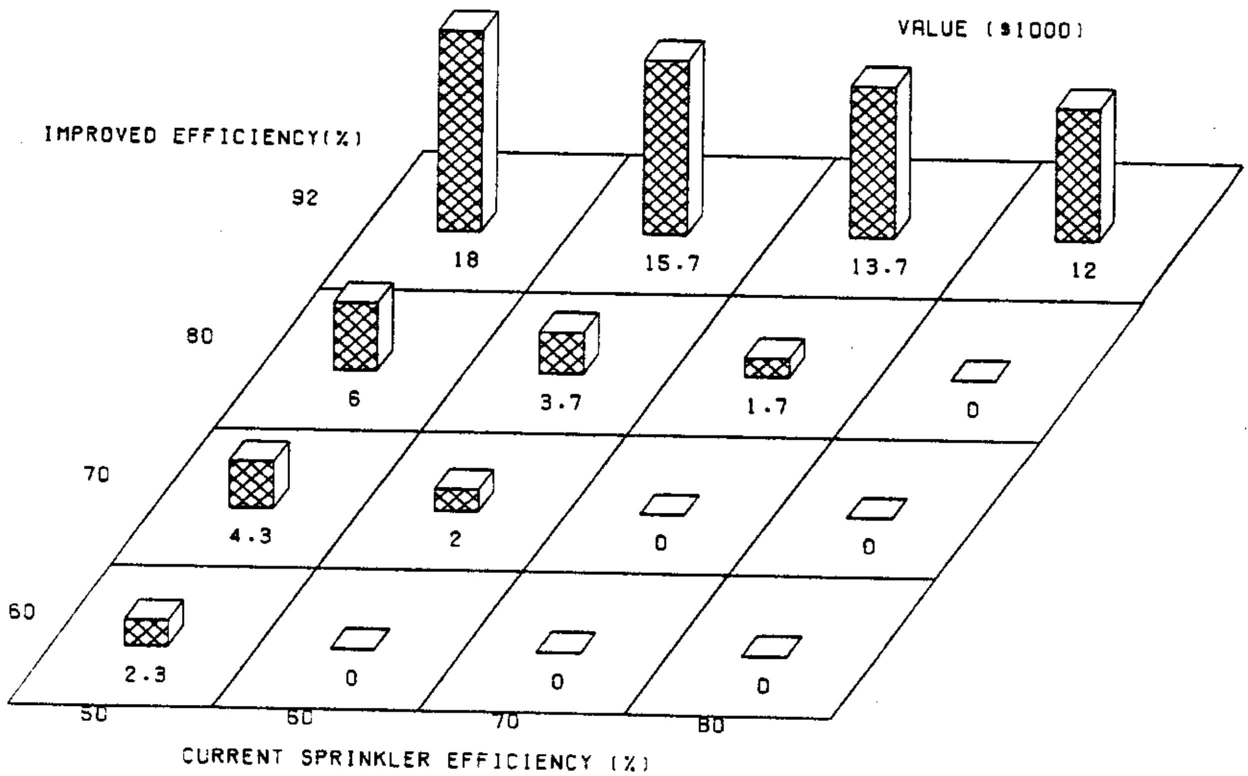

Figure B-11. Discounted Present Value for 160 Acres of Improved Sprinkler Efficiency: Northern High Plains.[a]

[a] Assumes an initial 77 ft. saturation thickness, 82 ft. lift, 6% discount rate over a 20 year planning horizon and low crop prices. The values listed are the maximum that could be expended to improve sprinkler efficiency from X% to Y%.

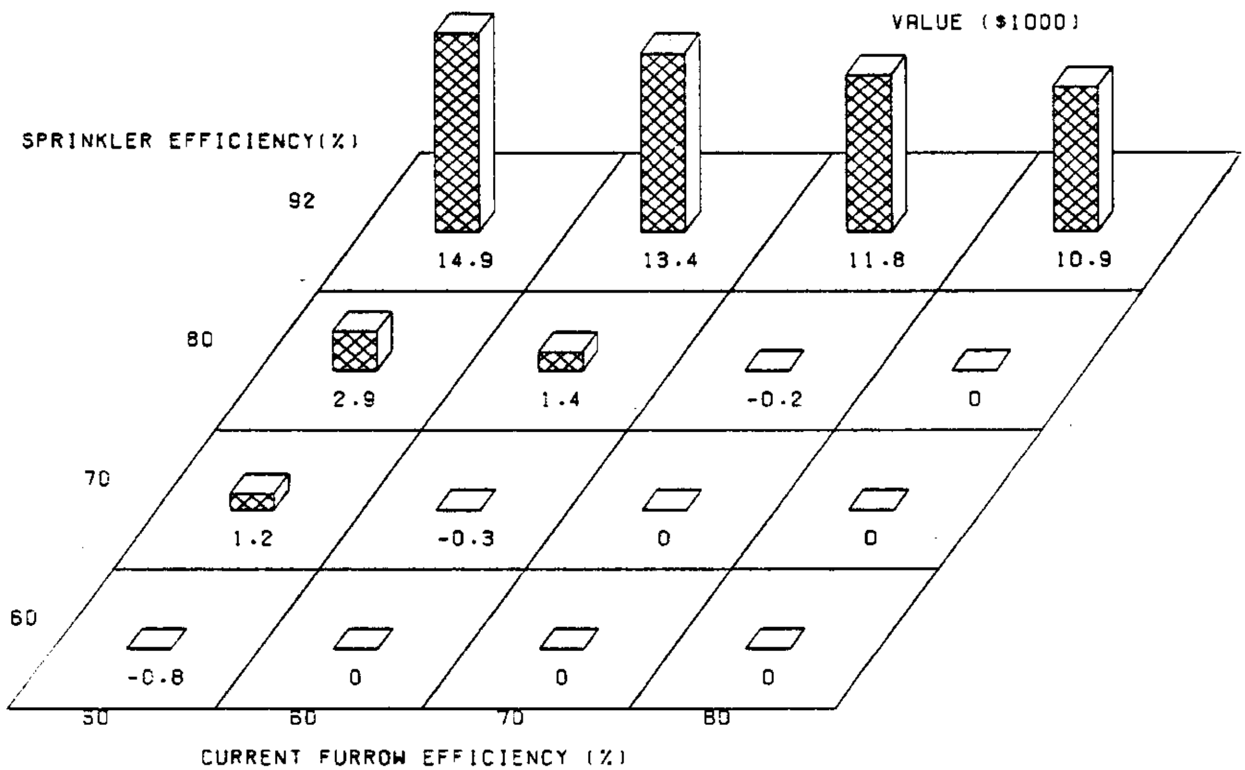

Figure B-12. Discounted Present Value for 160 Acres of Improved Irrigation Efficiency From Furrow to Sprinkler: Northern High Plains.[a]

[a] Assumes an initial 77 ft. saturation thickness, 82 ft. lift, 6% discount rate over a 20 year planning horizon and low crop prices. The values listed are the maximum that could be expended to improve irrigation efficiency from X% to Y%.