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NATURAL GAS POWERED IRRIGATION ON THE TEXAS HIGH PLAINS:
The Economic Feasibility of Replacing Pump Parts to Improve Efficiency

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INTRODUCTION

General Problem Statement

In the 1975 growing season on the Texas High Plains[1] crop acreage totaled 10,568,000 acres, and 55 percent of this acreage was irrigated. Sixty-six percent of all irrigation power units on the Texas High Plains operate on natural gas; a total of 46,154 units (21).

The Agricultural Engineering Department at Texas Tech University randomly tested forty-six natural gas irrigation pumping units on the Plains area in 1967 and found the average pumping efficiency running at 56.65 percent with a range of 26.6 percent to 80 percent. Most of these pumps are operating far below their potential efficiency (1).

Pumping costs per acre-foot of water are affected by: (1) the price of natural gas, (2) the pumping lift, and (3) the overall pumping plant efficiency. Since 1973, the price of natural gas per thousand cubic feet increased 162.5 percent on the Texas High Plains (24). Natural gas prices are expected to continue to increase in the future at about the same rate (9). Since natural gas is used in the production of electricity on the Texas High Plains, switching power sources is not necessarily the solution to combat rising natural gas prices.

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[1] The Texas High Plains is a 40 county region described in the 1975 High Plains Irrigation Survey published by the Texas Agricultural Extension Service. Figure 1-1 also illustrates this region.

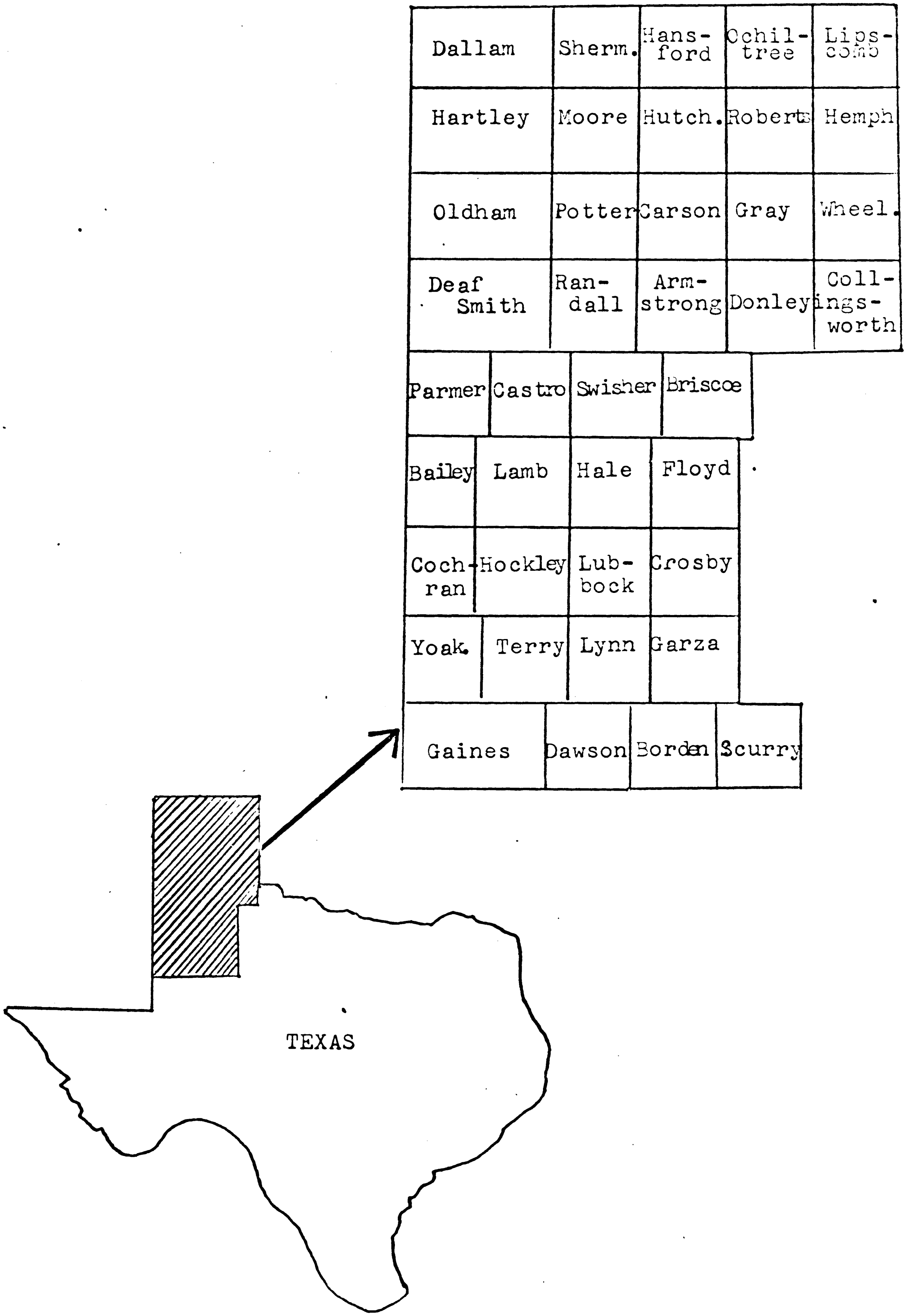

Figure 1-1: Counties Included In The Texas High Plains Study And Their Location

Throughout the Texas High Plains, most of the water available for irrigation comes from an underground formation called the Ogallala Aquifer. Relatively small amounts of water are available from surface sources. The decline in the available unrenewable underground water supply is evidenced by the constant increase in lift affecting all irrigation wells in the Texas High Plains. "Lift" is the number of feet water must be raised to bring it to the surface, and as lift increses, energy consumption per acre-foot (and cost) rise rapidly. The combination of increased pumping lift and increased natural gas prices causes pumping costs to escalate even more rapidly and the individual irrigation farmer can do little to control either of these factors.

The individual irrigation farmer can, however, implement programs to maintain a high level of overall pumping efficiency. Some factors which affect efficiency and which can be controlled by the operator are: (1) proper installation of correctly designed parts for the pumping unit and, (2) replacing the pump bowls as they become worn.

Specific Problem Statement

Irrigation farmers in the Texas High Plains are faced with dwindling underground water supplies and increasing expenditures for production inputs. Since most irrigation units in the area are natural gas powered, the steadily rising cost of this fuel input has a significant effect on the farmer's "cost-price squeeze".

In the past, when the well yield declined because of groundwater depletion, the typical operator adjusted the motor in order to maintain his desired well yield. As the throttle settings of a natural gas engine depart from the specified settings, the resulting decrease in thermal efficiency of the engine results in greater fuel consumption per hour of engine operation. Pump parts were generally not replaced or repaired throughout the life of a system.

Today, when natural gas price is of major concern in the operation of an irrigation plant, the efficiency of the pump as well as the engine needs to be monitored in an effort to restore overall pumping efficiency. This entails repairing or replacing pump bowls at the correct time, that is, when the cost of additional fuel consumption associated with using worn pump bowls or mismatched pump components is equal to the cost of replacing the bowls. In this way, the user can attempt to avoid incurring excessive pumping costs.

Objectives of the Project

The general objective of this project is to evaluate the energy cost savings of adopting alternative replacement programs for a representative natural gas irrigation pumping plant in the Texas High Plains under conditions of rising natural gas prices.

More specifically the objectives are to:

1. Determine the cost of replacing pump bowls over the useful life of the pumping plant
2. Determine the total cost of pumping 240 acre-feet of water for each year over the useful life of the pumping plant for three alternative natural gas prices
3. Determine average cost per year of pumping 240 acre-feet of water over the useful life of the pumping plant for three alternative natural gas prices
4. Determine the optimum time to increase pump efficiency by replacing pump bowls over the useful life of the pumping plant for three alternative natural gas prices

Methods and Procedures

Since all of the objectives of this report were calculated for a representative natural gas pumping plant, the first step was to determine the characteristics of a representative plant in the Texas High Plains. Parmer County in the Southern High Plains was considered to have hydrologic conditions diverse enough to typify all of the Texas High Plains. Therefore, the most of the data used to determine a characteristic pumping plant for the Texas High Plains was based on data previously determined for Parmer County (16).

In order to choose the appropriate pump to fit the hydrologic conditions of a representative pumping plant, the data for Parmer County was presented to Mr. Don Smith of the High Plains Underground Water Conservation District and he suggested the correct number of stages and the appropriate type of pump for the given lift, depletion rate, and yield.

To determine Objective 1, the estimated cost of pump bowls and their installation was obtained from Stewart and Stevenson, Irrigation Engineers.

The present average cost to the High Plains irrigation farmer of natural gas was determined from Pioneer Natural Gas Co. and this price along with two higher prices were the three natural gas prices used in determining Objectives 2 and 3.

To determine Objective 4, the cost of pumping 240 acre-feet of water per year associated with pump inefficiency was determined. This cost was added to bowl replacement cost and accumulated through each year from 1976 to 1996. Each one of these values was divided by the year number in order to determine average specified costs. The optimum to replace pump bowls is when the average specified cost to pump 240 acre feet of water is at a minimum for each of the three natural gas prices used.

Review of Literature

General background information on irrigation practices and problems was derived from the following literature:

Anonymous, Groundwater and Wells, Edward E. Johnson, Inc., Saint Paul, Minnesota, 1966.

This publication is a reference book for the water-well industry. It is primarily concerned with the engineering aspects of wells and discusses the applications of different types of irrigation equipment. Chapter 6, which discusses pumps, defines all of the terms associated with pumping water and illustrates the various pump parts.

Clover, Vernon T. General Economic Aspects of Utilization of Underground Water for Irrigation in High Plains of Texas. Texas Tech University, School of Business Administration, 1961.

This study brings together the economically significant facts concerning the use of underground water for irrigation in the Texas High Plains. It also analyzes the general economic implications of these conditions.

Osborn, J.E., Holloway, M., and Walker N. Importance of Irrigated Crop Production to a Seventeen County Area in the Texas High Plains. Texas Tech University, Department of Agricultural Economics, Technical Publication T-1-101, May, 1972.

This report delineates the dependency of the economy of the Texas High Plains upon the irrigated production of cotton, grain sorghum, and wheat, It also projects the economic effects of the continuing decline in groundwater supply on the Texas High Plains. This study provides quantitative measures of potential decline in net revenue due to insufficient availability of irrigation water and therefore provides data to support the view that a problem exists for the whole community with regard to water depletion in West Texas.

Relevant economic theory, computation methods and other problem solving techniques have been reviewed from the following publications:

Dunford, W.J., & Rickard, R.C. "The Timing of Farm Machinery Replacement", Journal of Agricultural Economics, XV, No. 3 (1961) 348-58.

Dunford and Rickard provide an example of tractor replacement policy. It shows minimum average cost per hour occurring at the point of tangency of a line from the origin with the holding cost curve. Holding cost is defined in this study as the initial cost plus repairs and is plotted with dollars on the vertical axis and hours of use on the horizontal axis. Holding cost in this example is the same concept as specified cost in the Texas High Plains study.

Faris, J. Edwin. "Analytical Techniques Used in Determining the Optimum Replacement Pattern", Journal of Farm Economics, XLII, No. 4 (1960) 755-66.

This paper presented techniques used in determining when to replace certain types of assets. In determining the optimum replacement pattern for beef and peach production, Faris has detailed discounting and compounding procedures which may also fit other types of replacement problems, for example, replacement problems which do not involve maximization of revenue. This Faris problem was approached in terms of maximizing revenue over time where the maximization analysis shows that the asset should be held to the point where marginal revenue is equal to average revenue. This is similar to marginal cost equalling average cost in a cost minimization analysis.

Howard, Ronald A. Dynamic Programming and Markov Processes. New York: Wiley & Sons, 1960.

This text discusses optimal replacement time and cost minimization problems. It also includes the probability of breakdown in this type of analysis when it discusses machinery replacement, therefore, it is probably more realistic than a similar study by Danford and Rickard which does not discuss the possibility of breakdown in a machinery replacement problem.

Chisholm, Anthony H. "Criteria for Determining the Optimum Replacement Pattern," Journal of Farm Economics, XLVIII, No. 1 (1966), 107-12.

This article defines the general objectives of replacement problems. It states that the primary aim is to select the particular production period over which a specified planning horizon will yield the maximum net present value of future profits. To accomplish this goal the main problem is of correctly specifying all the cost elements, both actual and opportunity. The detailed discussion of opportunity costs helps to identify all of the opportunity costs involved in the cost-minimization problem being studies on the Texas High Plains.

Slavin, Albert, and Reynolds, Isaac N, Basic Accounting, Hinsdale, Illinois: The Dryden Press, 1975.

This basic accounting textbook details different methods for calculating depreciation, compound interest, discounting and present value, all of which are necessary in calculating costs over a number of years.

The following studies have been directed to irrigation supply costs on the Texas High Plains:

Agricultural Engineering Department, Texas Technological College. Power Requirements and Efficiency Studies of Irrigation Pumps and Power Units. September 1, 1968.

This research project was conducted on 134 irrigation plants within a 400-mile radius of Lubbock. A representative cross section of pumping plants were tested considering size, type, make, age, energy source, and physical condition. Pump efficiencies were measured and found to average 52 percent with a range from a very low 6.2 percent to an upper limit of 82 percent. The study condluded that the wide variation in cost of pumping water was due to; lowering of the water level, badly worn pumping equipment, lack of proper maintenance of the power unit and improper design and/or installation of equipment.

William F. Hughes, Bureau of Agricultural Economics, USDA. Cost of Pumping Water for Irrigation Texas High Plains, Texas Board of Water Engineers, August, 1951.

This is one of the earliest studies of irrigation costs conducted on the Texas High Plains. It provides some historical data on the early development of irrigation in this area as well as cost of pumping water per acre-foot. This study does not include measurements of pump efficiency in calculating cost therefore, comparisons of cost at that time with today's costs would not appear to be of any value since costs are also dependent on the efficiency of the pumping unit.

William F. Hughes and A.C. Magee, Some Effects of Adjusting to a Changing Water Supply, Texas Agricultural Experiment Station Bulletin 966, October 1966.

Hughes and Magee detailed in this study some of the adjustments that producers make when water supply changes. It includes practices such as irrigation of every other row, less costly pumping techniques, closed water distribution systems, increased hours of pump operation, and staggered planting dates. This study also includes information on decline of the water table, well yields and other related water supply data for the Texas High Plains.

W.F. Hughes, et al., Economics of Wtater Management for Cotton and Grain Sorghum Production, High Plains, Texas Agricultural Experiment Station Bulletin 931, May, 1959.

Hughes determined that variations in total cost per acre-foot between irrigation units with similar total amounts of pumpage reflect (1) operating costs as they are affected by the size of well yield, type of fuel or energy used, and well efficiency and (2) differences in the amount of fixed costs that result from differences in the amount invested in individual plants. The study determined that most irrigation wells, pumping at least 100 acre feet of water, delivered water at a total cost somewhere between $5.00 and $9.00 per acre foot. It should be noted, however, that these costs were computed in 1959.

Robert E. Whitson, Costs of Pumping Water for Irrigated Farms--Southern High Plains of Texas--1966, Unpublished M.S. Thesis, Department of Agricultural Economics, Texas Tech University, Lubbock, Texas, June, 1967.

This thesis developed water supply and pumping cost information pertinent to long-range irrigation planning by Southern High Plains irrigation farmers. Pumping costs were developed for each of seven alternative power sources including natural gas. Whitson notes that the declining water table has resulted in "(1) reduced output per well, (2) decreased number of acres irrigated per well, and (3) increased pumping lifts". A useful comparison might be to compare the prices of irrigation equipment and fuels as well as irrigation pumping technology which were determined in this 1967 study with prices and practices of irrigating in 1976.

CHAPTER II

CONCEPTUAL FRAMEWORK OF THE PROBLEM

The primary cost minimization system being dealt with in this report is that of increasing the overall plant efficiency by increasing the pump efficiency. The pump loses efficiency because of wear on the bowls resulting from sand particles carried in the water and from corrosion from chemicals in the water[1]. The principal cause of loss of pump efficiency on the Texas High Plains is that of depletion in the water table. Over a number of years of normal use, the overall plant efficiency of a natural gas well would decrease as shown in Figure 1.

The amount of natural gas used to pump one acre-foot of water is:

$$MCF = \frac{(.00318)\ (LIFT)}{OPE} \qquad (1)$$

where

MCF = thousands of cubic feet of natural gas

.00318= thousands of cubic feet of natural gas required to lift one acre-foot of water one foot at 100 percent overall pumping efficiency.

LIFT = vertical lift in feet, and

OPE = overall pumping efficiency

The overall pumping efficiency of a well powered by natural gas decreases as a result of loss in efficiency in the pump assembly and/or loss in the efficiency of the engine. As may be seen from the above equation, as the OPE decreases, MCF increases and cost of pumping water also increases. This relationship is demonstrated by Figure 2.

It may be seen from Figure 3, which is a combination of the previous two figures, that if no measures are taken to maintain or improve overall pumping efficiency, as the number of years over which the well is being operated increases, overall pumping efficiency decreases. In terms of economic theory, this situation would exist when a short-run profit objective is being pursued by the irrigation farmer. The producer may hold fixed costs constant each year in order to try to obtain the same net profit

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[1] Scott Hathorn, Arizona Pumpwater Budgets 1976, Cooperative Extension Service, The University of Arizona, Tucson, Arizona, p. 24.

each year without regard to the long-run consequences of not maintaining the equipment. Fixed costs include investment cost or the new cost of irrigation well parts, interest on investment, and labor used to install the well parts. Therefore, if pump bowls are replaced, total fixed costs will increase by the cost of this new investment. If pump bowls are replaced "n" times during the life of the pumping plant, total fixed costs will increase by "n" times the cost of the bowls. Figure 4 illustrates the effect of replacing pump bowls on total fixed costs.

Total Variable Costs

The total variable costs of pumping water vary with the output of the irrigation pumping unit. As more water is pumped, more variable costs are incurred. Variable costs may also be referred to as operating costs in this instance because, by definition, they are the costs of operating the pumping plant. They include fuel or energy cost, lubricating oil, repairs, maintenance and labor costs to operate the plant. As long as pump bowls are not replaced, overall pumping efficiency (OPE) will decrease gradually as illustrated in Figure 1. When OPE decreases, natural gas requirement increases as illustrated in Figure 2 and Equation 1. The cost of natural gas is a component of total variable costs therefore, when pump bowls are not replaced over the life and operation of the pumping plant, total variable costs increase. When OPE is increased by changing the pump bowls, total variable costs decrease as shown in Figure 5a.

Over time, total variable cost initially increases. When pump bowls are replaced, total variable cost drops back to its original level and then, as efficiency decreases, total variable cost increases once again but with a steeper slope than previously. The total variable cost increases at a faster rater after each bowl replacement because even though efficiency is replaced to its original level, lift goes on increasing and, referring back to Equation 1, it may be seen that as lift increases, fuel requirements and consequently, variable costs increase. The total variable cost curve over time is illustrated in Figure 5b.

Total Costs:

Total cost of pumping water for any period of time is the sum of total fixed costs and total variable costs for that period. Before any bowl replacement takes place in a given year, total fixed costs are relatively low and total variable costs increase toward the end of the year because at that time the declining OPE becomes most significant as well as the drop-off in lift. Total fixed costs increase and total variable costs decrease if bowls are replaced and OPE improved during that year. From this it is hypothesized that total costs before bowl replacement are less than total costs after bowl replacement up to a certain level of inefficiency, depending on replacement rate. After the pump loses more efficiency variable cost to pump water increases to the extent that total cost before bowl replacement exceeds total cost after bowl replacement. A hypothetical example of these costs is illustrated in Figure 6.

Average Cost

In order to determine the point in the life of the pumping plant where costs can be minimized by replacing pump bowls, average costs of pumping water need to be developed. Average cost is defined as total cost divided by units of output and it is known that the replacement policy that minimizes cost occurs where average cost is at a minimum.

Specified Costs

In this case, specified costs are defined as total fixed costs plus the variable costs associated with pump inefficiency. The other variable costs are omitted because they are assumed to be independent of age. Fig. 7 shows assumed total fixed costs and specified costs. Minimum average cost per year is indicated by the point of tangency of a line from the origin with the specified cost curve. When a vertical line is drawn from this point of tangency to the horizontal axis which shows years, this point on the horizontal axis shows at what year bowls should be replaced in order to minimize average cost.

TSC_1 = Total Specified Cost at Initial Gas Price.

TSC_2 = Total Specified Cost with Increased Gas Price.

X_1 = Minimum average Cost associated with TSC_1.

X_2 = Minimum average Cost associated with TSC_2.

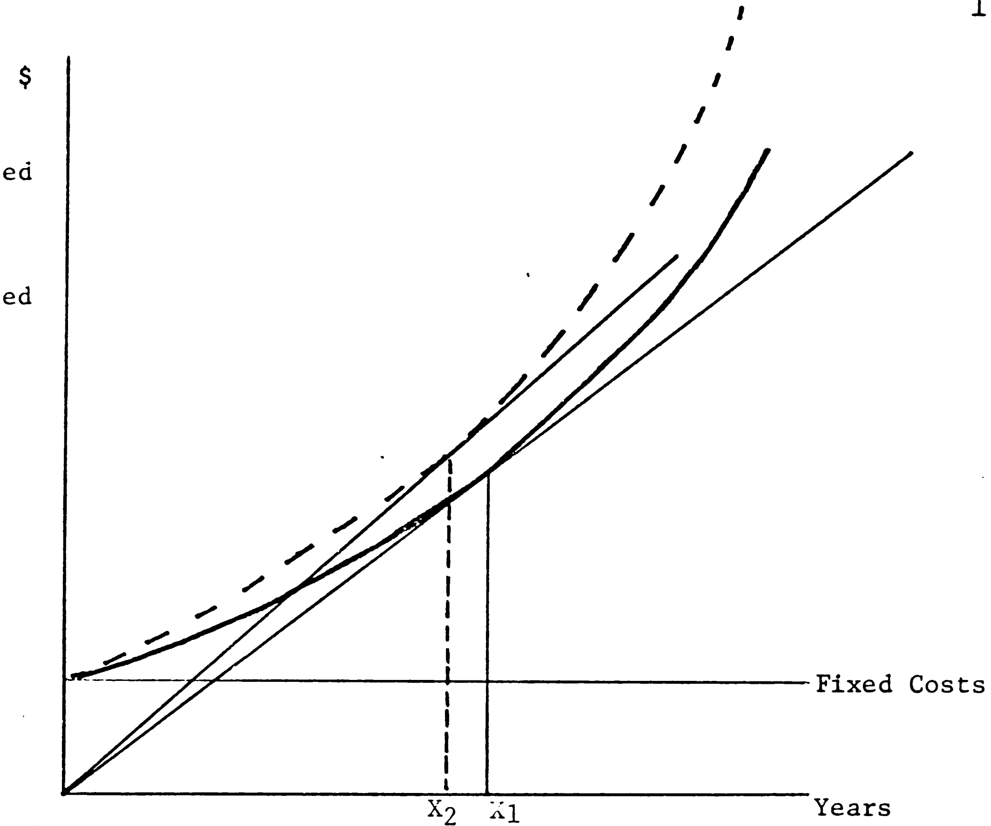

Fig:2-7a: Change in Total Specified Cost With Increased Fuel Cost

TSC_3 = Total Specified Cost When Cost of Bowl Replacement Increases and Fuel Price Does Not Change.

X_3 = Minimum average Cost Associated with TSC_3

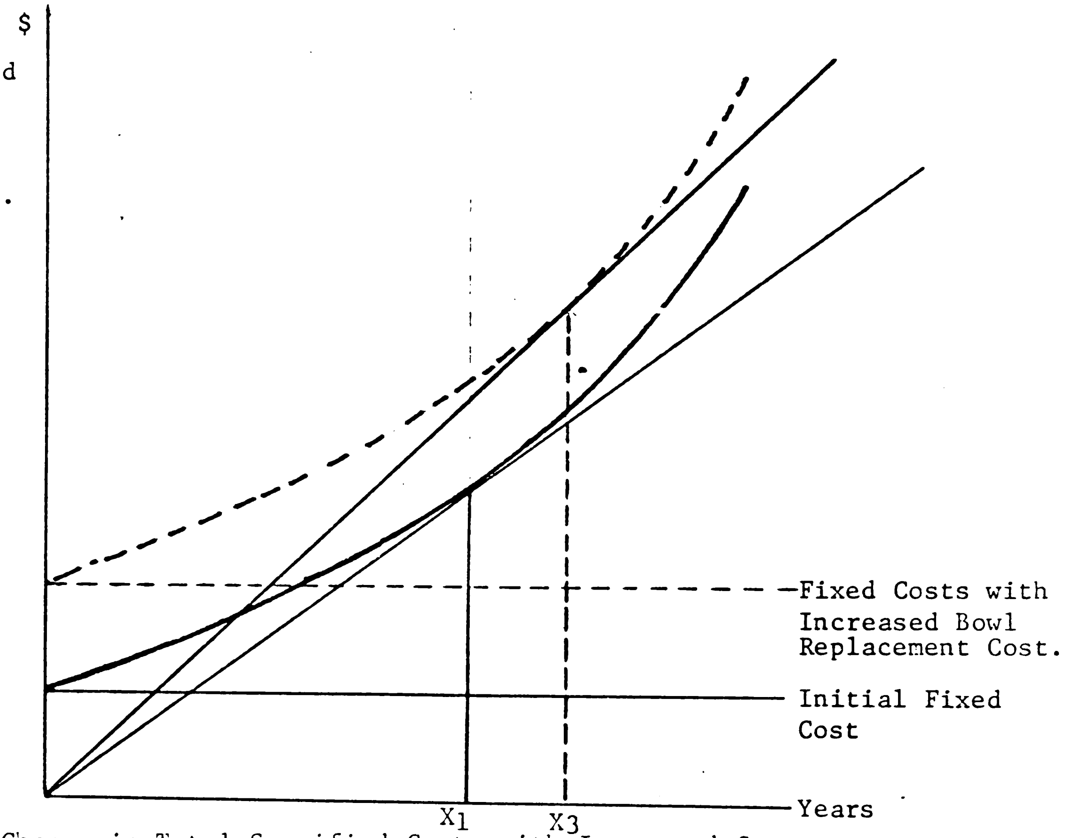

Fig:2-7b: Change in Total Specified Costs with Increased Cost of Bowl Replacement.

Effect of Increased Natural Gas Prices on Decision to Replace Pump Bowls.

Fuel cost is a major component of the total variable cost of pumping water, therefore, it is also a component of total specified costs. When fuel price increases, the part of variable cost of pumping water which is associated with pump inefficiency increases proportionately. Total specified costs with increased fuel price graphs as a more vertical curve; it shifts to the left of the original total specified cost curve. Therefore, the point of tangency of a line drawn from the origin occurs at an earlier point on the new total specified cost curve. The vertical line joining the point of tangency with the horizontal axis would also move to the left. It may be hypothesized from this that if fuel price increases and the replacement policy that minimizes cost is being employed, pump bowls would be replaced at an earlier year in the life of the pumping plant.

Effect of Increased Bowl Replacement Cost on Decision to Replace Pump Bowls.

Should any of the components of fixed cost increase, such as retail price of pump bowls, or labor charge to install bowls, then total specified cost would also reflect this increase. The new total specified cost curve would shift upward and to the left of the old total specified cost curve though both total specified cost curves would be parallel. The point of tangency of a line drawn from the origin would occur at a later stage on this new total specified cost curve. The optimum replacement policy, therefore, with increased replacement cost would be to replace bowls at a later year in the life of the pumping plant.

CHAPTER III

METHODS AND PROCEDURES

Introduction

This chapter shows how the problem of diminishing pump efficiency has been worked through in order to determine, first, the characteristics of a representative pumping plant. It shows where the data were found and the costs involved in pumping 240 acre feet of water with this representative pumping plant under different natural gas prices and different efficiencies. The cost of replacing pump efficiency is also shown here. The information found in this chapter will permit an irrigation farmer to evaluate the energy cost savings which may be achieved by improving pump efficiency.

A Representative Pumping Plant

Special Report No. 19 by the Agricultural Engineering Department, Texas Tech University (1) determined that 66 percent of all irrigation power units on the Texas High Plains operate on natural gas. Therefore, it was decided that carrying out this research on a natural gas powered irrigation plant was most representative of the area being studied.

Parmer County in the Southern High Plains of Texas is considered to have hydrologic conditions diverse enough to typify all of the Texas High Plains (16). Consequently, most of the data used to determine a representative natural gas pumping plant for the Texas High Plains was based on Parmer County data. This data was taken from High Plains Underground Water Conservation District No. 1 publication entitled Ogallala Aquifer Water-Level Data With Interpretation, 1965-1974.

Lift and Total Dynamic Head: The average depth to water in feet in the Ogallala Formation as projected through the year 1998 in Parmer County, Texas, was taken from page 18 of the Ogallala Aquifer Water-Level Data With Interpretation, 1965-1974. This is shown graphically in Figure 3-1 and also in column 2, Table 3-1. The depth to water in feet, or Lift as it is more commonly called, is the level at which water is lowered in a well when pumping is in progress. However, Total Dynamic Head (TDH) is the actual head that the pump is operating against because this measurement is the sum of Lift as previously defined, plus the pressure head, friction loss in the column and discharge pipe, and volocity loss. These additions to lift were estimated to cause the equivalent of 2.3 additional feet of depth to water per pound of pressure (24). Pressure at the head was estimated to be 10 pounds, therefore, a constant figure of 23 was added to the projected Lift for each year. This calculation is shown in column 3, Table 3-1.

Saturated Thickness: Texas Water Development Board Report No. 205 showed saturated thicknesses in Parmer County in the Southern High Plains as projected from 1974 through 2020 by computer techniques. In 1976, the estimated average saturated thickness was found to be 102.94 feet.

Yield: The estimated number of gallons of water per minute (GPM) that can be pumped, given the preceding average conditions of lift and depletion rates defines yield. To estimate yield in gallons per minute from the one assumed level of saturated thickness, it was assumed: (1) that the yield of each pumping well was 800 GPM except as limited by the capacity of the aquifer (this conforms with the historical trend of equipping new wells with 8-inch or smaller pumps);

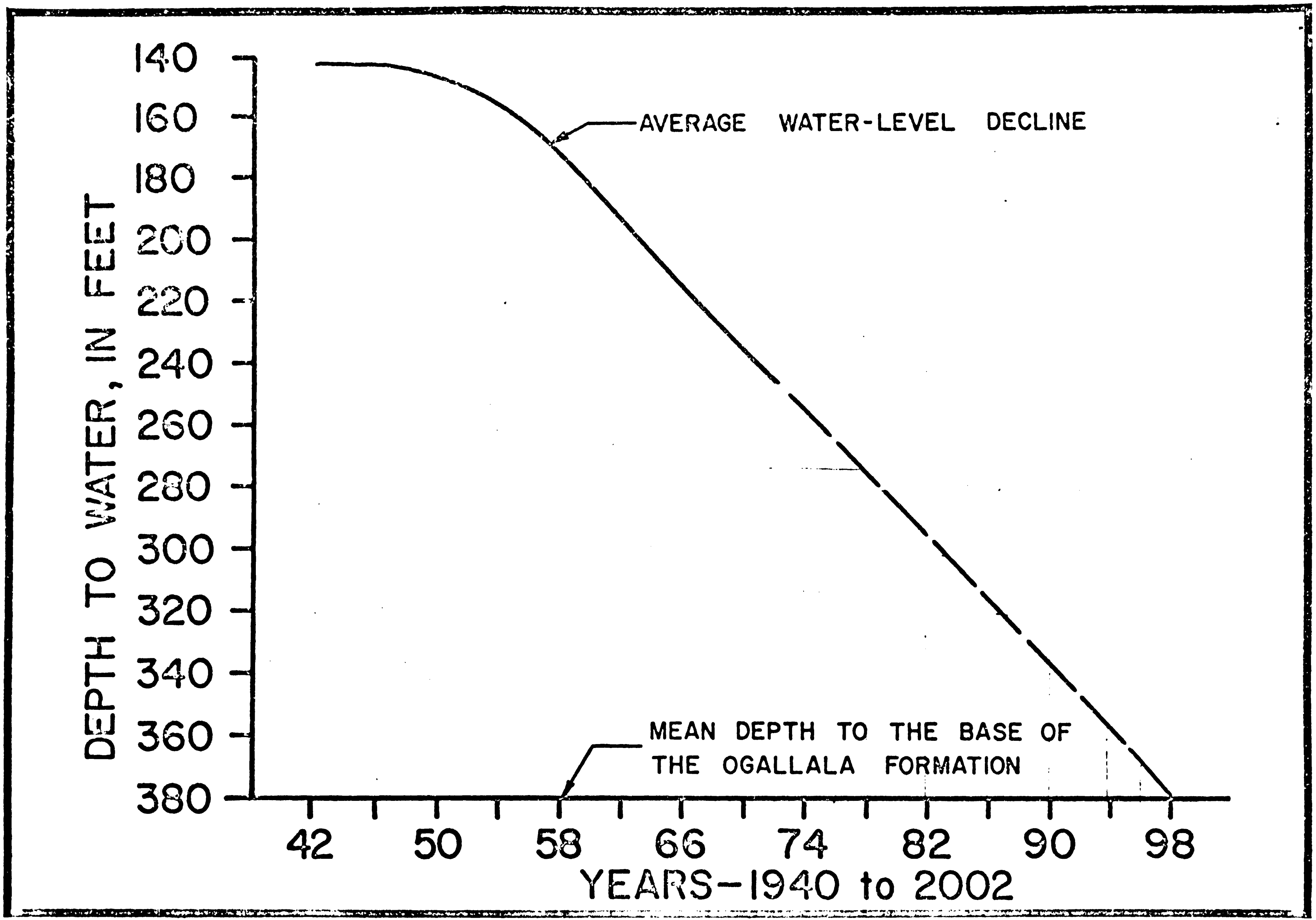

FIG: 3-1 —AVERAGE DECLINE OF THE WATER TABLE IN THE OGALLALA FORMATION AS EXTRAPOLATED TO THE YEAR 1998, PARMER COUNTY, TEXAS.

Source: Ogallala Aquifer Water-Level Data, With Interpretations, 1965-1974, High Plains Underground Water Conservation District No. 1, Lubbock, Texas, June, 1974

TABLE 3-1

CHARACTERISTICS OF A REPRESENTATIVE NATURAL GAS PUMPING PLANT ON THE TEXAS HIGH PLAINS

					Annual Change In Pumping Efficiency Due To:			
Year n	Average Depth To Water	Average Total Dynamic Head	Average Yield	Efficiency Of The Pump	Changing Hydrologic Conditions	Wear And Tear On Pump	Net Efficiency Of The Pump	Net Overall Plant Efficiency
	(Feet)	(Feet)	(GPM)	(%)	(%)	(%)	(%)	(%)
1976	260	283	697.00	67.0	0	0	67.0	12.67
1977	265	288	650.02	65.0	- 2	-1	62.0	11.70
1978	270	293	608.97	63.0	- 1	-1	61.0	11.53
1979	275	298	569.26	61.5	- 1	-1	59.5	11.25
1980	280	303	530.89	59.0	- 2	-1	56.0	10.59
1981	286	309	493.86	56.5	0	-1	55.5	10.49
1982	293	316	458.16	55.0	- 1	-1	53.0	10.02
1983	300	323	423.81	52.5	- 1	-1	50.5	9.55
1984	305	328	390.79	50.0	- 1	-1	48.0	9.07
1985	310	333	363.41	47.0	- 2	-1	44.0	8.32
1986	315	338	337.01	45.0	- 2	-1	42.0	7.94
1987	320	343	311.62	42.0	- 1	-1	40.0	7.56
1988	326	349	287.21	40.0	- 1	-1	38.0	7.18
1989	333	356	263.81	38.0	- 2	-1	35.0	6.62
1990	340	363	241.39	35.0	- 2	-1	32.0	6.05
1991	345	368	219.97	33.0	- 2	-1	30.0	5.67
1992	350	373	208.49	31.0	- 2	-1	28.0	5.29
1993	355	378	197.16	30.0	- 1	-1	28.0	5.29
1994	360	383	186.44	28.0	0	-1	27.0	5.10
1995	365	388	175.88	26.5	- 2	-1	23.5	4.44
1996	370	393	165.62	25.0	- 2	-1	22.0	4.16

(2) that the specific well yield is 7.5 gallons per minute per foot of saturated thickness; and (3) that the saturated thickness falls off 10 feet for seasonal fluctuation. Consequently, yield for 1976 was determined to be 697 GPM. This was found by multiplying 102.94 (the given saturated thickness in feet) minus 10 feet, times 7.5 GPM (16).

To predict the well's future capacity, well yields resulting from continued depletion were calculated by use of the following formula[1]:

$$Q_t = Q_{t-1}\left(\frac{T_t}{T_{t-1}}\right)^2 \qquad (1)$$

Where:

Q_t = Present well yield in gallons per minute,

Q_{t-1} = Original well capacity in gallons per minute,

T_t = Present saturated thickness in feet, and

T_{t-1} = Original saturated thickness in feet.

The authors of <u>Projected Economic Life of Water Resources, Subdivision No. 1, High Plains Underground Water Reservoir</u> note that the above equation was designed to measure the effects of water level change on well output in uniform aquifers. They also state:

> "Aquifers in the High Plains are not uniform. Thus, the calculated well yield, in any given year, is subject to error. Over time, however, the available evidence indicates that the use of this equation provides estimates of well yield that are in close agreement with existing well yields" (page 60).

To project the well yields from 1976 through 1996, present saturated thickness in feet (T_t) was treated as the saturated thickness in the year the projected well yield is calculated. This saturated thickness measurement is taken from

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[1] This equation was obtained from <u>Texas A & M University, Technical Monograph No. 6</u> and was developed by W. L. Broadhurst, formerly Chief Engineer for High Plains Underground Water District No. 1.

Texas Water Development Board Report 205, page 6. Original saturated thickness (T_{t-1}) is considered as the 1976 measurement; 102.94 feet. Original well capacity (Q_{t-1}) is taken to be the 1976 calculated yield explained above; 697 feet. Therefore, present well yield (Q_t) is calculated as in the following example for the year 1996 when saturated thickness is projected to be 50.18 feet:

$$Q_t = 697\left(\frac{50.18}{102.94}\right)^2 = 165.62 \qquad (2)$$

Column 4 of Table 3-1 lists all of the predicted average yields calculated as in Equation (2).

Pumping Efficiency: The efficiency at which an irrigation pump operates is largely dependent upon the appropriate pump being professionally installed to fit the existing hydrologic conditions of the well. Because of this, the preceding characteristics of a representative pumping plant were submitted to Mr. Don Smith, Geologist, High Plains Underground Water District No. 1, Lubbock, and he was asked to suggest the correct pump design to match these characteristics. In view of the estimated depletion rate, Mr. Smith recommended a Layne Pump with 7 stages. The particular efficiency curve at which this pump operates with one bowl setting is shown by Figure 3-2. Part of this pumping curve diagram was expanded in Figure 3-3 to show the efficiency at which this particular pump would operate with seven stages to pump the number of gallons per minute for each year predicted from 1976 to 1996 in Column 4, Table 3-1.

From Figures 3-2 and 3-3, the annual depletion in pumping efficiency was listed in Column 5, Table 3-1. This drop off in efficiency was attributed only to the drop-off in the water table. In discussing the problem of pump inefficiency with Dr. W. Ulich, Professor of Agricultural Engineering, Texas Tech University (22), he suggested that an irrigation pump also loses a certain amount of efficiency each year simply through wear and tear. Therefore it was estimated that deducting an additional constant one percent from efficiency per year of operation would more accurately portray a true picture of diminishing efficiency in irrigation pumps. This calculated is shown in Column 6, Table 3-1 and the net efficiency of the pump per year is shown in Column 8 of the same table.

Net Overall Plant Efficiency: This is defined as the percent efficiency of the entire pumping plant in converting the amount of natural gas energy into useful work output. In some studies, the term "overall pump efficiency" is used interchangeably with "overall plant efficiency" which leads to confusion between this measurement of entire efficiency of the plant and that of efficiency of the pump only. Thus, in this study, "net overall plant efficiency" is used specifically to describe the product of net pump efficiency X motor efficiency X gearhead ~~efficiency~~.

Net pump efficiency was calculated in the previous step and is shown in Column 8, Table 3-1. Motor efficiency of 19.9 percent was considered to be a constant and was found by averaging the motor efficiencies of 25 natural gas engines used in pumping irrigation water on the Texas High Plains. These efficiencies were reported in *Power Requirements and Efficiency Studies of Irrigation Pumps and Power Units* (1). Gearhead efficiency of natural gas irrigation plants was tested and reported to average 95 percent in *Arizona Pumpwater Budgets, 1976* (10). Therefore, this figure was adopted as a constant for use in calculating net overall plant efficiency in this Texas High Plains study. Net overall plant efficiency is shown in Column 9, Table 3-1.

Energy Cost to Pump 240 Acre Feet Of Water in the Texas High Plains.

Dr. K. B. Young of the Department of Agricultural Economics, Texas Tech University (24) determined for another study that the average quantity of water

LOWER	4.5	1
LOWER	2.5	2
LOWER	1.5	3
AS IS	0.0	5

NOTE: ANY CHANGE IN EFFICIENCY CHANGES EITHER THE HEAD OR HORSE POWER IN PROPORTION.

LAYNE & BOWLER INC.
Memphis, Tenn.

1750 RPM

SINGLE STAGE LABORATORY
HEAD & HORSE POWER
THRUST "K" = 3.0

Figure 3- 2: Official Efficiency Curve for Representative Pump Operating With One Stage.

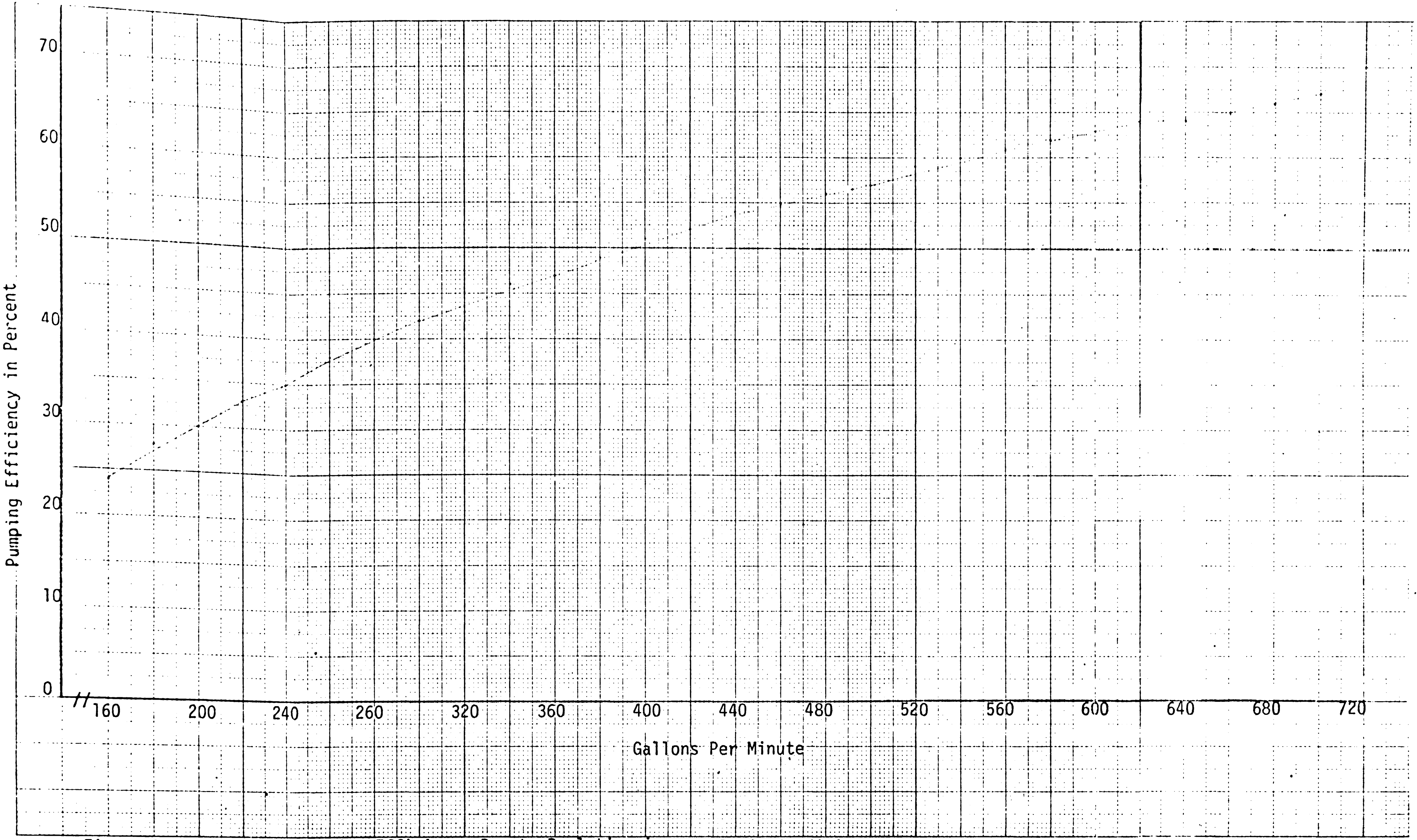

Figure 3-3: Change in Pumping Efficiency Due to Depletion in Hydrologic Conditions

pumped per year by irrigated crop producers in the Texas High Plains approximates 240 acre feet. Therefore, energy costs to pump this quantity of water per year for 20 years were calculated, at three different natural gas prices.

Pioneer Natural Gas Company supplies more than 90 percent of all natural gas used in irrigation plants in the Texas High Plains. The price of natural gas per thousand cubic feet (MCF) differs according to the quantity used. The larger the quantity of natural gas used by the producer, the lower the price per MCF. Pioneer Natural Gas Company was asked to estimate the average cost per MCF of natural gas to irrigation farmers in the study area and they reported an average price of $1.23 per MCF (9). However, since gas prices are expected to increase considerably in the next 20 years, the cost of pumping 240 acre feet of water was also calculated, given gas prices of $1.50 and $2.00 per MCF, as well as $1.23 per MCF.

The amount of natural gas required to pump one acre foot of water was calculated by the following formula:

$$\text{MCF} = \frac{(.00318)\ (\text{TDH})}{\text{OPE}} \qquad (3)$$

where .00318 = thousands of cubic feet of natural gas required to lift one acre-foot of water one foot at 100 percent overall pumping efficiency.

TDH = vertical lift in feet plus 23 feet, and

OPE = overall plant efficiency expressed as a decimal.

The answer to the above equation was multiplied by 240 to give the amount of natural gas required to pump 240 acre feet of water and then multiplied by the cost per MCF. The Total Dynamic Head and Overall Plant Efficiency for each year were taken from Columns 3 and 9 of Table 3-1. The calculated energy costs for each year, given 3 alternative natural gas prices,are reported in Table 3-2.

TABLE 3-2

TOTAL VARIABLE COSTS, TOTAL FIXED COSTS, AND TOTAL SPECIFIED COSTS[1] TO PUMP 240 ACRE-FEET OF WATER WITH A REPRESENTATIVE NATURAL GAS IRRIGATION PLANT ON THE TEXAS HIGH PLAINS

Year	Energy Cost to Pump 240 AF Water Given The Following Natural Gas Prices Per MCF:			Initial Cost of Bowls	Increase in Energy Cost Due To Lowered Pump Efficiency Given The Following Natural Gas Prices:			Cumulative Specified Costs Given The Following Natural Gas Prices Per MCF:		
	$1.23	$1.50	$2.00		$1.23	$1.50	$2.00	$1.23	$1.50	$2.00
	Dollars									
1976	2096.78	2557.05	3409.40	1710	0	0	0	1710.00	1710.00	1710.00
1977	2310.73	2817.97	3757.29	1710	176.90	215.74	287.65	1886.90	1925.74	1997.65
1978	2385.51	2909.16	3878.88	1710	214.64	261.75	349.00	2101.54	2187.49	2346.65
1979	2486.61	3032.45	4043.26	1710	278.69	339.87	453.15	2380.23	2527.36	2799.80
1980	2685.90	3275.49	4367.32	1710	440.94	537.73	716.97	2821.17	3065.09	3516.77
1981	2765.20	3372.19	4496.26	1710	475.78	580.22	773.63	3296.95	3645.31	4290.40
1982	2960.48	3610.35	4813.80	1710	619.20	755.13	1006.84	3916.15	4400.44	5297.24
1983	3174.99	3871.94	5162.59	1710	781.84	953.47	1271.29	4697.99	5353.91	6568.53
1984	3394.77	4139.96	5519.95	1710	964.58	1176.31	1568.42	5662.57	6530.22	8136.95
1985	3757.20	4581.95	6109.27	1710	1289.96	1573.12	2097.50	6952.53	8103.34	10234.45
1986	3996.13	4873.33	6497.77	1710	1491.85	1819.33	2425.76	8444.38	9922.67	12660.21
1987	4259.08	5194.00	6925.33	1710	1717.75	2094.82	2793.09	10162.13	12017,47	15453.30
1988	4562.94	5564.56	7419.41	1710	1977.16	2411.16	3214.88	12139.29	14428.65	18668.18
1989	5048.19	6156.33	8208.44	1710	2410.54	2939.69	3919.58	14549.83	17368.34	22587.76
1990	5623.42	6868.80	9158.40	1710	2933.91	3588.91	4785.21	17483.74	20957.25	27372.97
1991	6092.68	7430.10	9906.79	1710	3366.12	4105.03	5473.36	20849.86	25062.28	32846.33
1992	6619.06	8072.03	10762.71	1710	3855.46	4701.78	6269.05	24705.32	29764.06	39115.38
1993	6707.79	8180.23	10906.98	1710	3907.14	4764.80	6353.08	28612.46	34528.86	45468.46
1994	7049.72	8597.22	11462.96	1710	4212.03	5136.62	6848.82	32824.49	39665.48	52317.28
1995	8203.37	10677.46	13338.81	1710	5328.63	7171.68	8664.44	38153.12	46837.16	60981.72
1996	8868.35	10815.06	14420.08	1710	5956.56	7264.10	9685.47	44109.68	54101.26	70667.19

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[1] Specified Costs Are Defined Here as Initial Cost of Bowls Plus Energy Costs Associated With Pump Inefficiency.

Determining Optimum Time To Replace Pump Bowls.

In order to determine the optimum time to replace pump efficiency, the energy costs of pumping water associated with the pump's inefficiency, and the cost of replacing the efficiency by installing new pump bowls, were determined.

Energy Costs Associated With Pump Inefficiency: The probable increases in energy costs due to lowering of the pump's efficiency were found by using Equation (3), but with a constant overall plant efficiency of 12.67 percent and subtracting the energy costs with decreasing overall plant efficiency from each answer. These solutions are shown in Table 3-2. A constant overall plant efficiency of 12.67 percent was used for this calculation because this was found to be the maximum efficiency under the given conditions in Table 3-1.

Bowl Replacement Cost: Mr. Don McElroy, Sales Engineer, Stewart & Stevenson Irrigation Services, Inc. supplied the following cost specifications for replacing pump bows in an irrigation pump similar to the pump recommended by the High Plains Underground Water Conservation District geologist.

Bowl Assembly = \$1,229.60
Installation Labor = \$2.00 per foot of bowl settings

Stewart & Stevenson recommended that the bowls be set at 240 feet and installation labor was figured at \$2.00 per foot of bowl settings, therefore, the cost of removal and reinstallation is \$2.00 x 240 = \$480. It was assumed that the bowls have zero salvage value.

Total Specified Costs: The sum of increased energy costs due to lowered pump efficiency and bowl replacement cost was defined here as total specified costs. These costs were also accumulated over 20 years and are shown in Column 5, Table 3-2.

Average Specified Costs: Since it is known that the optimum time to replace pump bowls is when average cost is at a minimum,each total cumulative specified cost shown in Table 3-2, Column 5 was divided by the number of years pumping to determine the average specified cost of pumping 240 acre feet of water for each year between 1976 and 1996. These costs are shown in Table 3-3 where it may be seen that the minimum average cost occurred soonest for the costs determined using the highest gas price. Average specified cost is also the slope of total specified cost.

TABLE 3-3

AVERAGE OF CUMULATIVE SPECIFIED COSTS TO PUMP 240 ACRE FEET OF WATER WITH A REPRESENTATIVE NATURAL GAS IRRIGATION PLANT ON THE TEXAS HIGH PLAINS, GIVEN THREE ALTERNATIVE NATURAL GAS PRICES.

Year	$1.23	$1.50	$2.00
	$	$	$
1976	1710.00	1710.00	1710.00
1977	943.45	962.87	998.83
1978	700.51	715.83	782.22
1979	595.06	631.02	699.95
1980	564.23	613.02	703.35
1981	549.49	607.55	715.07
1982	559.45	628.63	756.75
1983	587.25	669.24	821.07
1984	651.40	725.58	904.11
1985	695.25	810.33	1023.45
1986	767.67	902.06	1150.93
1987	846.84	1001.46	1287.78
1988	933.79	1109.90	1436.01
1989	1039.27	1240.60	1613.41
1990	1115.58	1397.15	1824.87
1991	1303.12	1566.39	2052.90
1992	1453.25	1750.83	2300.91
1993	1589.58	1918.27	2526.03
1994	1727.61	2087.66	2753.54
1995	1907.66	2341.86	3049.09
1996	2100.46	2576.25	3365.10

CHAPTER IV

FINDINGS

The findings of this study evaluated bowl replacement cost, energy cost to pump 240 acre feet of water at three alternative natural gas prices, average cost per year to pump 240 acre feet of water, and the optimum time to replace pump bowls on the Texas High Plains for a representative natural gas pumping plant between the years 1976 and 1996.

The characteristics of this representative pumping plant were found to be as follows:

Power Source: Natural Gas
Annual Average Quantity of Water Pumped: 240 Acre Feet
Average Depth to Water in feet: 260 - 370
Average Total Dynamic Head in feet: 283 - 393
Average Yield in Gallons Per Minute: 697 - 166
Average Net Overall Plant Efficiency in Percent: 12.67 - 4.16

The cost of purchasing bowl assembly was determined to be $1229.60 and installation labor was found to cost $480. Therefore, total bowl replacement cost was determined to be $1709.60. This figure was rounded to $1710.

As the distance to water from the surface increased over the 20 years of the study, and the overall plant efficiency decreased, it became progressively more expensive to pump the same quantity of water. Using the current average natural gas price of $1.23, the cost of pumping 240 acre feet of water increased from $2096.78 in the first year to $8868.35 in the last year of the study. Using the projected natural gas prices of $1.50 and $2.00 per MCF, it was found that the cost of fuel to pump 240 acre feet of water increased from $2557.05 to $10815.06 and from $3409.40 to $14420.08 respectively over 20 years.

The increases in energy costs which occurred in response to lowered pump efficiency only, were calculated for each of the three natural gas prices and the results of this calculation are plotted in Figure 4-2.

The annual cost per year to pump 240 acre feet of water was calculated and the minimum average specified cost occurred in the 6th year of operation when natural gas prices were assumed to be \$1.23 and \$1.50 per thousand cubic feet, and in the 4th year of operation when natural gas price was assumed to be \$2.00 per thousand cubic feet.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

This study determined that:

1. Net pumping efficiency of a representative new natural gas powered irrigation pump on the Texas High Plains will drop off an average of 45 percent over the next 20 years if pump efficiency is not restored.

2. The cost of replacing pump efficiency by changing pump bowls set at 240 feet is $1710.

3. The cost of pumping 240 acre feet of water per year will increase from $2096.78 in 1976 to $8868.35 in 1996 when the price of natural gas is assumed to be $1.23 per thousand cubic feet. The cost will go from $2557.05 in 1976 to $10815.06 in 1996 when the price of natural gas is $1.50 per MCF, and from $3409.40 in 1976 to $14420.08 in 1996 when natural gas price is $2.00 per MCF. These increased costs are due to the combination of lowered pumping efficiency and increased lift.

4. The costs of pumping 240 acre feet of water per year accumulated over 20 years of operation due to lowered efficiency of the pump only are as follows:

(a) $42399.68 when costs are calculated with natural gas price of $1.23 per thousand cubic feet or an average of $2119.98 per year.

(b) $52391.26 when costs are calculated with natural gas price of $1.50 per thousand cubic feet or an average of $2619.56 per year.

(c) $68957.19 when costs are calculated with natural gas price of $2.00 per thousand cubic feet or an average of $3447.86 per year.

Conclusions

It is concluded from this study that under typical Texas High Plains conditions, energy cost savings may be achieved by replacing pump bowls in natural gas irrigation pumps within the 20-year life of the pump when the price of natural gas is $1.23 per thousand cubic feet or higher.

More specifically, it becomes economical to restore pump efficiency by replacing pump bowls in the 6th year of operation when the price of natural gas is $1.23 or $1.50 per thousand cubic feet, and in the 4th year of operation when the price of natural gas is $2.00 per thousand cubic feet.

It was hypothesized in Chapter II that if fuel prices increased and the replacement policy to minimize operating costs was being employed, pump bowls would be replaced at an earlier year in the life of the pump. Due to the results of this study leading to the above conclusions, this hypothesis is accepted. It is also noted, however, that if the cost of replacing pump bowls increased, the optimum time to replace bowls would occur in a later year.

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