LIMITED IRRIGATION CROP SELECTION: A LINEAR PROGRAMMING MODEL

by

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CHAPTER I

INTRODUCTION

"Linear programming is a computational method to determine the best plan or course of action, among many which are possible, when there are many alternatives for the plan, a specific or numerical objective exists for it, and the means or resources available for attaining it are limited."(1) Ever since the inception of the method of linear programming, it has been applied usefully to varied sets of problems. The calculation of an optimal plan can be accomplished by linear programming provided the objective, the limited resources, and competing means of using resources in furthering the objective, can be quantified. A linear programming problem does not exist unless there are limited resources or other restrictions which limit how much can be produced.

STATEMENT OF PROBLEM

Currently the most limiting resource for agriculture in western Kansas is usable water for irrigation. The governor's task force on Water Resources estimates withdrawals from the underground water supply to average 14 times the recharge rate.(39) With this disparity between withdrawals and recharge, it seems apparent that measures be taken to efficiently use water. The overdraft (withdrawal exceeding recharge) is caused by the rapid development of irrigation. In 1977, irrigtion reached a peak of nearly 2.3 million acres of wheat, grain sorghum, corn, silage, soybeans, alfalfa and sugar beets. Nearly one-third of the harvested acres in the west is irrigated. The overdraft causes two problems affecting decisions regarding irrigation: (1) it causes an increase in irrigation costs because the water lift increases and (2) it causes well yield (gallons per minute pumped) to decrease because of a declining saturated thickness. A decrease in well yield influences crop selection and the timing and scheduling of irrigation. Full irrigation of alfalfa or corn requires a large volume of water delivered within a relatively short period to avoid stressing the crop and reducing its yield. As well yield declines, so does the ability to meet the crops' water needs during the critical growth and development phase; consequently, the farmer is confronted with either accepting lower yields or switching to crops that are more tolerant of stress caused by deficient soil moisture.

An irrigation farmer is faced with the interaction of the following variables; crop response to water, timing and scheduling of irrigation, acres under irrigation, well yield and the cost and returns from alternative crops and water management strategies. Of these variables, the farmer controls how much water to apply, when to apply water, number of acres to spread water and on the crops the water is to be applied.

Deep, friable silt loam soils, characteristic of western Kansas, compensate somewhat for the problem caused by reduced well yield. The Richfield, Kieth and Uysses soils have a water holding capacity of approximately 2.5 inches per foot of soil. Thus, a deep soil of 4-6 feet will store 8-12 inches of available soil moisture. As a well's yield decreases and the well is not capable of supplying the plants consumptive use, water is drawn from the soil received.

If well yield is capable of meeting the consumptive use needs of the plant, the problem of timing and scheduling irrigation does not exist. However, if a well is not capable of meeting these needs the farmer is confronted with the decision of applying less water per acre, maintaining the rate applied per acre but decrease acreage, adjust to alternative crops more tolerant of moisture stress or some combination of these choices.

OBJECIVES OF STUDY

The objective of this study is to develop a linear programming model to assist farmers in choosing the most profitable crops, the most profitable amount and time to irrigate and the most profitable acreage, assuming different well yields. Four crops are considered: wheat, corn, grain sorghum and soybeans. Thirteen combinations of the amount of water and timing or irrigation are considered for corn; seven combinations for soybeans, eight combinations for grain sorghum and six combinations for wheat. Well yield is varied from 200 to 1200 gallons per minute (GPM). Land size is held constant at 160 acres.

Every combination of water application and timing has an associated yield per acre for each crop. Irrigation cost are determined by feet of lift, the amount pumped per acre, and the GPM.

The amount of water required is specified for each stage of plant growth to meet the plants' needs to produce the yield specified.

The model selects the most profitable crops and combination of water application and timing for a 160 acre tract at different levels of well yield that meets the crops water requirements during specified periods.

The irrigation system is powered by natural gas, gated pipe conveyence to the field, and a tail water pit reuse system. A year of average rainfall was assumed in estimating water response of crop yield.

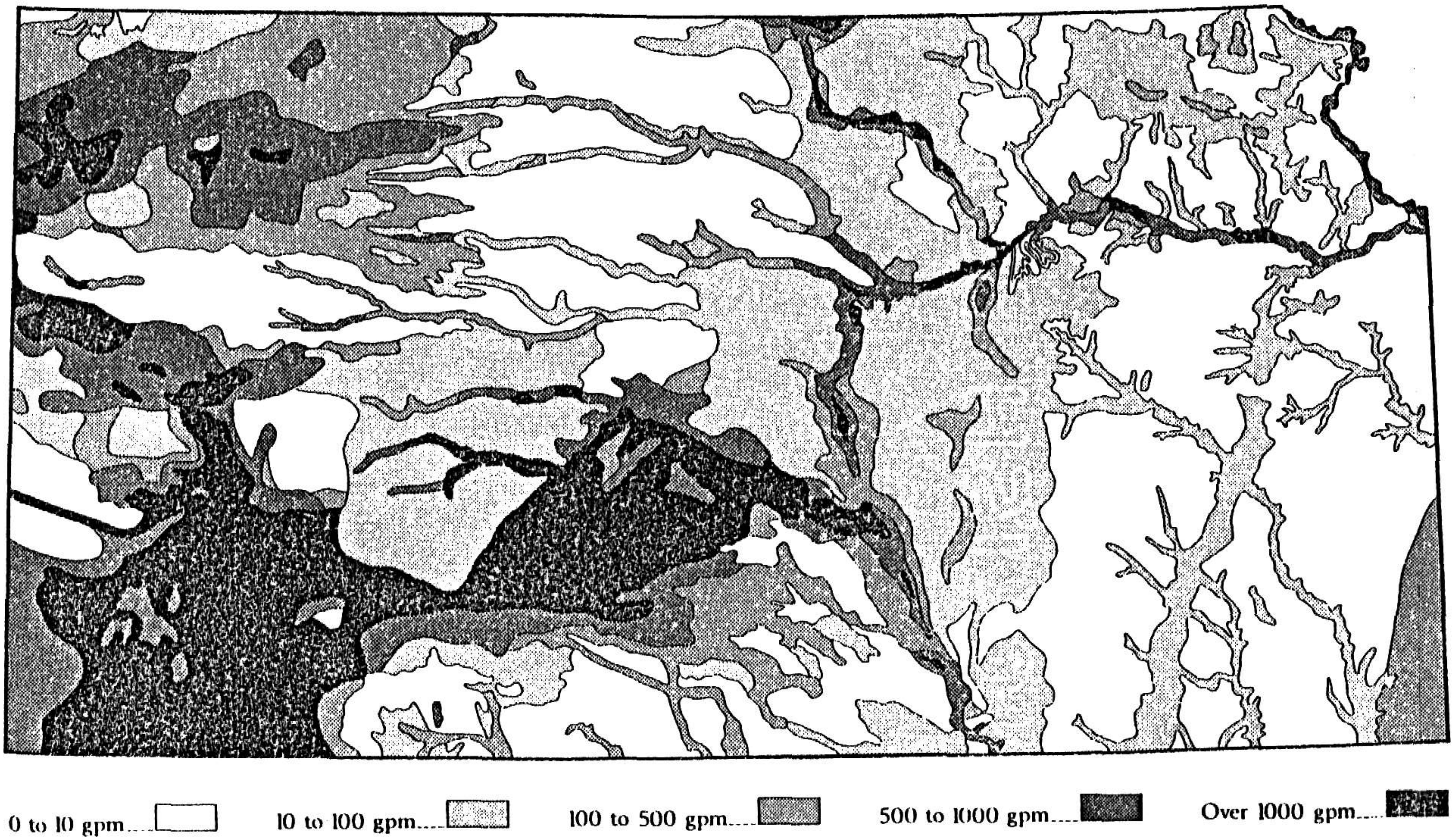

Figure 1. Map of Kansas Showing the Average GPM of Irrigated Wells.

CHAPTER II

REVIEW OF LITERATURE

The construction of a model that selects combinations of crops to be grown and the irrigation practice to be used involves an understanding of crop response to irrigation applied at different stages of plant growth and development. Economic and physiological growth models usually apply a specific crop and the weather conditions that exist in the experiment area. Although there are some computer simulation and linear program models to aid farmers in deciding how much water and when to apply it per specific crop, no model was found that considered scheduling water among alternative crops, size of field and well yield.

The effect of soil moisture variations on crop growth has been the subject of much research. Most of the early work reported was limited to studies of plant response to some arbitrary soil moisture level. Present work has changed though, with work being undertaken to study the effects on yield and plant development with severe soil moisture deficits at specific growth stages.

Kiesselbach (25) concluded that the amount of water used by any crop depends largely on the amount of vegetation and the duration and intensity of atmospheric demand for moisture. Timing of the irrigation with respect to critical water use periods, associated with the development of the plant may save water.

Kiesselbach discussed at considerable length the physiologic development of corn and a number of factors affecting it. He reported a rather fixed interval of time of about seven to eight weeks between fertilization and cessation of translocation to the ear which is considered the mature stage. With respect to soil moisture, Kiesselbach reported that severe early drought resulted in stunted size and delayed silking with many partially or completely barren plants. Drought following fertilization was observed to shorten the ear by drying back from the tip and by reduced kernel size due to destruction of productive tissue.

Experimental findings from a number of sources indicate that the growth stages of crops in which water deficits occur may have an effect on the relative yield response. Among those who have studied corn in this regard are Robins and Domingo (1953), Demmead and Shaw (1960), Barnes and Wooley (1969), and Downey (1972).

From a field experiment, Robins and Domingo (36) report that wilting conditions for only one to two days during the pollination period reduce corn yield as much as 22 percent and six to eight days about 50 percent. Demmead and Shaw (12) grew corn in five gallon crocks buried in the field (three plants/crock) and impossed acute water deficits during three growth periods and combination of these periods. Due to their uniform root volumes and method of measuring moisture stress it is probable each stress period represents nearly, the same absolute Evapo-Transpiration (ET) deficits. Making this assumption, moisture stress in the pollination period which they judged to be approximately equal to that imposed by Robins and Domingo again produced a 50 percent yield loss. The same stress during the late vegetative period reduced yield 25 percent, and during ear growth, 21 percent.

Barnes and Wooley (4) grew corn in plastic lined field trenches and imposed water stresses of equal severity at different stages of growth on a single-eared and a two-eared corn hybrid. Pollination period stress affected the single-eared hybrid significantly more than the two-eared hybrid which in effect has two chances to produce grain, somewhat separated in time. Downey (13) shows greatly reduced corn yields resulting from ET deficits in different growth stages, and agrees with earlier citations that the pollination period is most sensitive. He generalizes for nonforage crops including corn, grain sorghum, soybeans, and wheat, "that water stress at any time from flowering to maturity is undesirable and gives inefficient use of water."

Hall and Butcher (18) advance the postulate that crop water deficits in two or more time periods may reduce yield in multiplicate rather than additive fashion. Application of the principle depends on experimental determination of functional relations between water deficit and crop yield reduction in each major growth period over a range of water deficit levels.

Jensen (22) also suggests a multiplicative approach to yield prediction based on a series of predicatable ET deficits. In this approach, an exponent reflecting relative sensitivity to ET deficits must be determined for each major growth period. Jensen finds a linear relation between relative yields of grain sorghum and the product of the adjusted values for relative water use in various growth periods.

Hiler and Clark (20) develop an additive function termed Stress Day Index (SDI) for relation to yield when reduced by water deficits in more than one growth period. Two interrelated factors make up SDI, the first being a "stress day factor," equivalent to the growth period ET deficit expressed as a fraction of period ET max and the second being a "crop susceptibility factor," equivalent to the fractional reduction in seasonal yield which would be expected were there only the single period ET deficit. Like Jensen above, Hiler and Clark find a linear relation between yield of grain sorghum and their Stress Day Index.

The role of stored soil water in supplying some portion of the ET requirement of the crop in all parts of the season is not generally well understood. Neither is it well understood how soil textural anomalies at different depths influence stored soil water uptake in different growth stages, and consequently the requirements for irrigation.

Musick and Dusek (30) found moisture stress influenced grain sorghum yields primarily by (a) reducing the size and/or number of heads (the yield container) and (b) by limiting grain filling. Generally, the grain filling period is the more critical stage for decreasing yields unless severe stress earlier in the season greatly reduces the yield container. Head size is determined prior to heading and can be reduced by moisture stress during vegetative development. However, the yield container can still be increased after heading by irrigation stimulating tillers to develop heads and mature grain. Highest irrigation water-use efficiencies in their studies were associated with individual irrigations that occurred either when irrigation water was applied during dry periods when little or no rainfall occurred or when longer irrigation intervals were used during periods when appreciable rainfall occurred and generally involved treatments that incurred some moisture stress and slight to moderate yield reductions. Maintaining adequate water treatments for high yields lowered irrigation water-use efficiency associated with some individual irrigations. Maximizing irrigation water-use efficiency in combination with seasonal rainfall permitted applying fewer irrigations and using an early irrigation cut off date when significant rainfall occured during grain filling.

In a study at the Southwestern Great Plains Research Center at Bushland, Texas, Musick and Dusek (30) showed irrigation timing to be critical when less than an optimum amount of water is applied to winter wheat. One well-timed spring irrigation was found to increase yield more than two poorly timed applications, and two well-timed spring irrigations increased yields more than three poorly timed applications, with the most critical period for adequate soil moisture being from boot through early grain filling. There was a negative linear response between the water-use deficit during that interval and yields. Moderate soil-moisture stress during the early spring was not found to be a cause of reduced yields if soil moisture was adequate during the critical period.

Robins and Domingo (37) also studied limited irrigation of spring wheat at Prosser, Washington, and found that relatively high soil-moisture stress before the booting stage of plant development did not reduce yields. However, severe moisture stress from heading to grain maturation significantly decreased yields.

Stewart, Pruitt and Hagan (41) found that maximizing crop production with limited irrigation water requires quantitative information about differential yield response to given levels of water deficit in each major growth period. The pollinaton period of corn is considered a "critical period" regarding available soil moisture. Their finding supports the idea that corn grain yield is especially vulnerable to water deficits during the pollination period, provided the crop has experienced little or no ET deficit in the late vegetative period, ending at first tassel. However, they found the susceptibility of corn yield to deficits in the pollination period to be greatly lessened if there have been prior deficits. This is expressed as a "conditioning" factor which is important to the planning of irrigation programs which, either by choice or by exigencies of water supply, include ET deficits during one or more major growth periods.

Stewart, et al. found that grain sorghum yield was less sensitive to ET deficits than corn, and there is no indication that a conditioning factor operates with this crop. Their work suggests the following guidelines for irrigating corn and grain sorghum with limited water.

1. The experiments uniformly indicate that beginning the season with the soil water potential high in all future rooting depths facilitates full and rapid development of the root system. This in turn (a) provides the greatest possible protection against sudden shocking increases in ET deficit intensity when water grows short, and (b) maximizes the contribution of stored soil water toward the ET max requirement of the crop in each growth period and for the season as a whole. Since the exploitation of stored soil water by an expanding root system is a continuing process throughout the season, this also reduces the irrigation requirement in every growth period, and particularly in the peak water use period.

2. Regardless of whether crop ET actual derives from soil water in storage at planting time, from rainfall during the growing season, or from irrigation, a very limited water supply will be utilized more efficiently by grain sorghum than by corn. Additionally, in this situation grain sorghum will produce grain with greater reliability, without requiring as careful control of irrigation dates and depths.

Such work, as previously cited, has been the foundation for economic studies in this field. These studies generally center on means to optimize the use of this scarce resource.

Mapp, Eidman, Stone, and Davidson (29) constructed a soil water prediction model for a commonly irrigated soil in the study area by using daily rainfall, evaporation and irrigation data; (1) to identify the critical stages of plant development of the major dryland and irrigated crops in the study area; (2) to simulate the effects of available soil water and atmospheric stress during critical stages of plant development on yield for the major dryland and irrigated crops in the study area; (3) to combine the models for the individual crops; (4) to develop a model for a farm firm, and, to illustrate the potential of such a model for analyzing agronomic and economic problems.

Mapp et al. used a representative farm and organization of the production area studied. The organization of production are divided into a series of crop blocks-four for irrigated grain sorghum, one for dryland grain sorghum, two for irrigated wheat, one for dryland wheat, two for irrigated corn grain and two for irrigated corn silage. Irrigation strategies are developed by dividing the crop year into five critical stages and letting irrigation priorities and irrigation strategies develop. This model was used to evaluate the effect of water-use regulation alternatives given unrestricted pumping, a quantity limitation or a water taxing arrangement.

Another study by Mapp and Eidman (27) considers several courses of action with respect to the declining of water storage in the Central Ogallala Formation. One plan is to ignore the divergence of costs and allow current rates of water application to continue and deplete the water supply at a rapid rate with a second course of action being an attempt to more closely align social and private costs by restricting the quantity of water each irrigator is allowed to pump during a crop year. A third course of action would be to more closely align private and social costs by a graduated tax levied on a per unit above a quantity limitation. There are other courses of action available, but this study was limited to consideration of the above three.

A firm-level bioeconomic simulation model has been developed by Mapp and Eidman (28) capable of stochastically determining yields for the major dryland and irrigated crops in the central basin of the Ogallala Formation as a function of soil moisture and atmospheric stress during critical stages of plant development. This model also is used to evaluate three methods of regulation groundwater irrigation. Results differ for poor and adequate water situations but indicates the potential value of an education program on timing of irrigation application to maximize net farm income.

Buller and Roth (10) completed a study that examined the relationships between water applied at different plant growth stages. Experiment station data was used in a multiple regression model to estimate the effect of an additional acre inch of water on yield when water was applied at various crop stages. This production function approach underlies the linear programming method but is not as comprehensive in the number of variables studied.

Anderson and Mass (3) developed a model to simulate an irrigation system to study irrigation scheduling on income on irrigated farms. The model considered the allocation of water from an irrigation district to farmers who made decisions about what crops to water and how much water to apply. The choice of crops and water application was not based on profit maximization.

Many studies have considered various aspects of the economics of irrigation; some emphasize timing, production functions, marginal productivity of water or irrigation systems. This study is different in that it is a profit maximizing model based on selecting the most profitable crops, acres of each crop, and timing of irrigation subject to limitations of land and water and time for applying water.

CHAPTER III

DEVELOPMENT OF THE MODEL

Linear Programming Concepts

Linear programming is a mathematical planning technique that is often used in resource allocation problems or business decision problems. For a linear programming problem to exist, first there must be two or more decision alternatives which compete for scarce resources. More generally, there must be two or more decision alternatives that are interrelated because of constraints on the alternatives that are feasible. Second, there must be a normative goal with respect to the allocation process: for example maximize profits or minimize costs. Third, the characteristics of the decison problem must be "sufficiently" compatible with the formal assumptions of a linear programming problem. Perfect compatibility with assumptions is seldom achieved. Some judgement about what constitutes sufficient compatibility must be made. (4)

There are seven basic assumptions of a conventional linear programming problem. They are: (1) additivity of resources and activities, (2) linearity of the objective function, (3) nonnegativity of the decision variables, (4) divisibility of activities and resources, (5) finiteness of the activities and resources restrictions, (6) proportionality of activity levels to resources, (7) single-valued expectations.(1)

The property of additivity means that the sum of resources used by different activities must equal the total quantity of resources used by each activity for all resources, individually and collectively. Absence of any interaction among the activities of the resources is implied by this restriction. However, by proper formulation of the activities, interaction may be built into a model, even though the technical specification of variables in the model must adhere to additivity.

Nonnegativity of the variables is required. The model cannot allow growing a negative acreage of corn, or applying a negative quantity of irrigation water.

Complete divisibility of activities and resources is an assumption which implies that all resources can be used in fractional quantities. This is not a critical assumption for many inputs or resources such as 20.75 acres of land or 4.28 acre inches of water. For problems requiring solutions in whole numbers, such as hiring a farm hand or not hiring a farm hand where rounding to the nearest integer may distort the optimum solution, a special technique of linear programming is used.

An optimal solution can be computed only if there is a finite number of alternative activities and resources restrictions. It is only realistic to suppose that a typical farm and agricultural sector situation always involves a finite number of activities and restraints.

Proportionality is a linear relationship in that each additional unit of output requires the same quantity of input. This assumption is a special case of the law of diminishing returns. However, when it is important to show diminishing returns, additional activities are used, with different combinations of resources used by each and each limited to a specific number of units.

Single valued expectations implies resource supplies, input-output coefficients, prices of resources and activities are known with certainty. The linear program will work on the basis of the judgement on prices and input-output relationships provided by the programmer. The results of the program will therefore be no better than the assumptions made by the programmer.

Mathematical Formulation

The mathematical form of a linear programming problem may be conveniently expressed as follows.(1)

Maximize: $Z = c_1X_1 + c_2X_2 + \dots + c_nX_n$

Subject to:

$$a_{11}X_1 + c_{12}X_2 + \dots + a_{1n}X_n \leq b_1$$
$$a_{21}X_1 + c_{22}X_2 + \dots + c_{2n}X_n \leq b_2$$
$$\vdots$$
$$a_{m2}X_1 + a_{m2}X_2 + \dots + a_{mn}X_n \leq b_m$$

and

$$X_1 > 0,\ X_2 > 0,\ \dots,\ X_n > 0.$$

The X_j's represent the levels of the decision variables. The b_i's c_j's and a_{ij}'s are constants and may be positive, negative or zero. The b_i's may be thought of as representing the amount of the ith resource available for allocation to the alternative decisions (of which there are n). The a_{ij}'s then represent the amount of the ith resource required or consumed by each unit of the jth activity. Z represents the measure of overall effectiveness of any given combination of activity levels (and therefore any given resource allocation). The c_j's represent the increase in Z that would result from each unit increase in the respective X_j's.

Purpose of Model Development

The combination of a declining water table and increasing energy cost have caused some fundamental changes in the economic structure of irrigated agriculture in southwestern Kansas. Farmers need help in defining the adjustments which can restore economic efficient use of resources. These adjustments are limiting irrigation water to critical periods of crops, switching to crops that are more tolerant to drought stress, or planting a combination of crops that require water at different periods to maximize profits.

Farmers need a method to help determine the proper adjustment of various crop acres given their potential yield with various water restrictions accurately and realistically. Linear programming is a method that can help, since this technique efficiently selects the strategy that will maximize profits for a given quantity of land, water and time constraints. To develop this model, a quarter section

(160 acres) field is used to represent a "typical" irrigated agricultural unit. The 160 acre unit is a common size for one well with a gravity flow, gated pipe system.

Characteristics, such as crop response to water during various periods, length and time of these periods, quantity of water available, depth of water for pumping, type of energy available to power the pump, cost of energy, and prices, are specified in the model. Careful selection of these characteristics allow the model to approximate actual farming conditions. The solution of the linear program model gives the optimal combination of crops, quantity and timing of water to apply that will maximize the farmers profits.

Sources of Information

Data used in the develpment of the model was derived from numerous sources. These sources are referenced at appropriate points throughout the paper.

Structure of the Linear Programming Model

A mathematical description of what a linear programming model does has been presented. Now a model will be developed to optimize crop selection and irrigation practices in southwestern Kansas under given constraints. A linear program model is a series of linear equations which show the relationship between production activities and resource constraints, subject to a given level of technology. The general equations in the model are described as follows: The objective function is;

$$\max Z = \sum_i p_i Y_{ij} - \sum_i \sum_j c_{ij} X_{ij} - \sum_i \sum_j d_{ip} P_{ip}$$

where p is the per unit selling price of crop i,

y is the number of units sold of crop i,

c is the variable cost per acre less pumping costs of crop i of amount of water applied in combination j,

X is the number of acres of crop i and combination j produced,

d is the cost per acre inch of supply water to crop i and the j combination,

P is the acre inches of water pumped on crop i and the j combination,

i = wheat, grain sorghum, corn and soybeans,

j = 13 combinations of amount and timing of of water on corn, 7 combinations on soybeans, 6 combinations on grain sorghum and 5 combinations on wheat,

p = the period supplying water.

Subject to the following constraints;

land equation

$$160 \leq \sum_i \sum_j 1X_{ij}.$$

Production transfer equation

$$\sum_i \sum_j y_{ije} X_{ije} < \sum_i 1Y_{ie},$$

where y is the yield per acre supplied by crop i,

e = 1,2,3,4 for each crop.

water pumping requirement
Plant stage of growth requirements equations;

$$\sum_i \sum_p j_{ipm} P_{ipm} < W_{ijm} X_{ijm},$$

where W is the acre inches required by crop i of combination j,

g is the net irrigation inches supplied by pumping one hour,

and m is the mumber of equations for the stages of growth.

For corn the stages are pre-season irrigation, 18 inch height, pre-tassel, silking, milk, soft dough and hard dough. For soybeans the stages are five intervals not specified by stage of growth. For grain sorghum the stages are pre-season irrigation, 12 inch height, boot, heading and dough. In wheat the stages are pre-season irrigation, joint, boot, flowering and milk.

Water supply equations are:

$$B_n < \sum_{i}\sum_{p} 1P_{ipn}$$

where B is the water available in period n in units of acre inch. B values are calculated by well yield (GPM) times minutes per day times number of days in period n divided by gallons per acre inch.

Figure 2 is a simplified and abridged visual description of the linear program model in a matrix form. There are 95 activities (n=95) and 50 resources (m=50) in the matrix. A complete description of the components of the linear program matrix is presented in Appendix A.

In Figure 2, the first row represents the objective equation which is being maximized. Resource equations are represented by the rows "crop-land", "July9-13", "July21-27". The other rows represented by "Corn", "Beans", "Corn-Silk", "Corn-Milk", and "Bean#1" are transfer equations. The "1" in column "1" and row "July9-13" shows that for every one unit of activity that is engaged in, one acre inch of water is used from the water resource supplied during July 9 through the 13th represented by row "July9-13". Also, by engaging in one unit of activity, eighty five hundreths of an acre inch of water will be supplied to the row

	Water pumping activities #1	#2	#3	#4	#5	Corn	Corn	Beans	Sell	Right
	Corn-silking	Corn-milk	Corn-milk	Beans Pd1	Beans Pd1	XXXXXXO	XXOXXXX	XXOXOX	Corn	Hand Side
Objectives	1.065-	1.065-	1.065-	1.065-	1.065-	85-	85-	51-	3.00	
Corn						135-	135-			
Beans								26.6-		
Cropland						1	1	1		160 (acres)
Corn-silk	-.85					6				
Corn-milk		-.85	-.85			6	6			
Beans#1				-.85	-.85			4		
July9-13	1			1						318 (acre/in)
July14-20		1			1					445 (acre/in)
July21-27			1							445 (acre/in)

Figure 2. Linear Programming Matrix

"Corn-silk" for use to the corn crop during the silking period. The water requirement is the amount the crop uses, thus the coefficient .85 represent the system efficiency in delivering water to the crop.

Resources Available

The objective of this model is to simulate irrigating 160 acres in southwestern Kansas. Resources required are land, labor, capital, and irrigation water necessary for agricultural production. The only resources that cannot be acquired are land and irrigation water. Labor and capital can be acquired as needed for a given price. Non-use of land is possible as is the use of land for various crop activities. The crops will require one acre of land except for fallow grain sorghum and fallow wheat which will require two acres to account for the fallow year.

Labor requirements are the hours needed to complete field and irrigation operations. No value is placed in the RHS of the labor equation, but an unlimited quantity of labor is available through a hiring activity for $4.00 an hour.

Capital for the models' activities is available in an unlimited quantitiy through a borrowing activity at a 14 percent interest rate. It is assumed that the capital for crop activities will be used for only one half of the year.

A crop's irrigation requirement is based on receiving an average annual rainfall of 19.51 inches. Therefore, the results of the model will be for a year with an average rainfall. During years of below normal precipitation, there will be a larger difference between full irrigated crop yields and limited irrigated crop yields not accounted for by the model. In years with above average rainfall, the opposite will be true, the difference between full irrigated crop yields and limited irrigated and fallow crop yields will be less than accounted for by the model.

Soil-Water-Plant Relationship

The importance of soil water storage and availability of water in crop production has long been recognized. Much research has been done to characterize the soil properties responsible for water absorption and retention. The soil-water-plant system is now treated as a continuous dynamic system where water moves through the soil to the plant root surfaces, into the root, through the plant and into the plant and into the atmosphere along a path of continuously decreasing potential energy. The removal of soil water depends not only upon its amount and energy state but also upon the plants ability to absorb water and the atmospheric demand for water from the plant. The amount of water that is sufficient for satisfactory plant production depends upon the crop's specie, and variety, stage of growth, and the marketable product.(22)

Soil structure is concerned with the size of mineral particles. Specifically, it refers to the relative proportion of particles of various sizes in a given soil. The heaviness of texture increases as particles become smaller.

Figure 3 shows the general relationship between soil moisture characteristics and soil texture. The wilting coefficient increases as the texture becomes heavier. The field capacity increases until the silt loams are reached, then levels off. These are representative curves. Individual soils would probably have values slightly different from those shown. The soil from which the data on crop yields under the various irrigation practices used in the model is a Richfield silty clay loam soil. The results from the model will only realistically represent crops grown on similar soil textures.

Activities

Activities (X's) of the limited irrigation model in southwestern Kansas are grouped into the following categories: irrigation water transfers, corn growing, soybean growing, grain sorghum growing, wheat growing, crop selling, and crop input purchases.

There are 52 activities that transfer irrigation water from the water resource rows to the transfer rows which supply the water to the crops during physiological stages of the crop's life cycle. These activities all are in units of acre inches of water.

An 80 percent field efficiency, considered realistic for a furrow system of flood irrigation with a recovery pit when good management practices are followed, is assumed for the model. Efficiency may be defined as the ratio of the quantity of water effectively put into the crop root zone

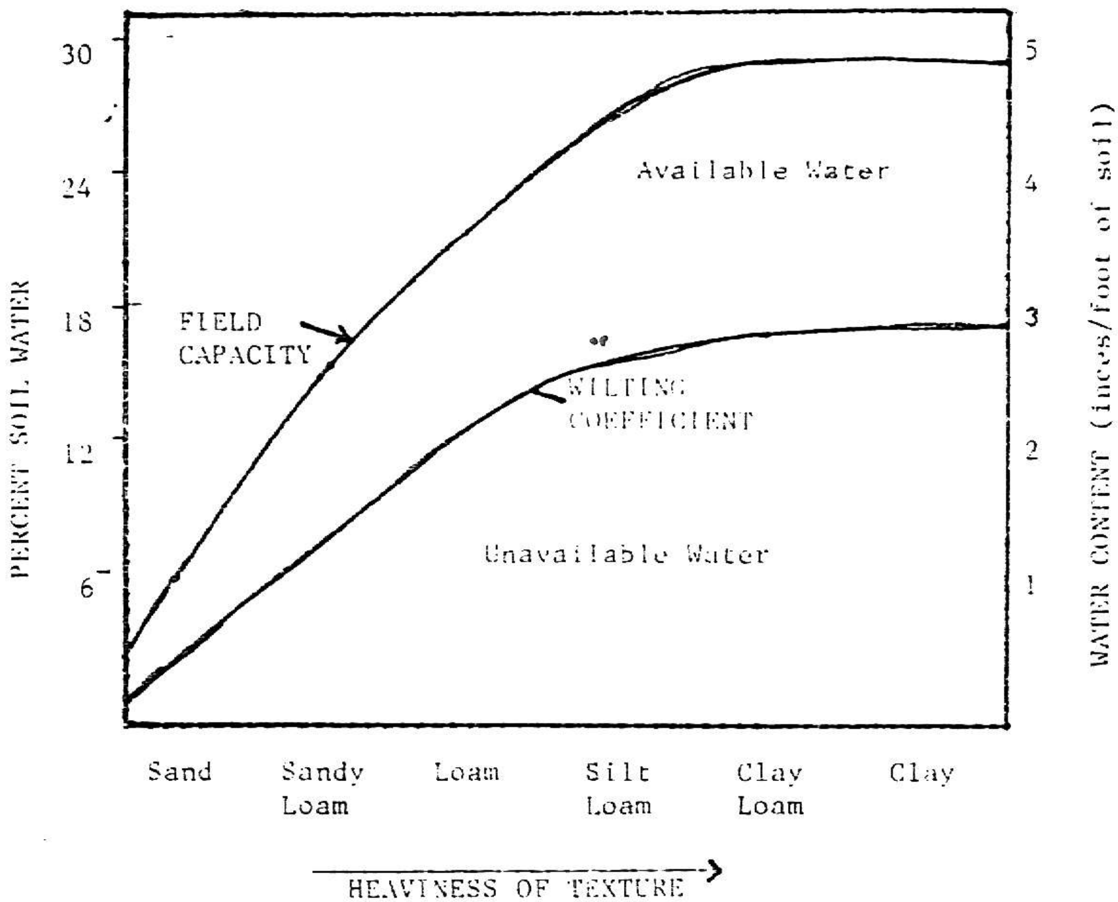

Figure 3. Percent of soil water available under different textures.

and utilized by growing crops to the quantity delivered to the field. It takes into consideration items such as evaporation, losses due to deep percolation, unequal distribution, and direct runoff. A 95 percent field efficiency for the experiment station data was recommended. A 5 percent field efficiency loss of the experiement station data is added to the 80 percent field efficiency assumed to adjust pumping requirements of the model. This is done in the matrix by placing a "1" in the column in the row in which the water is used and a ".85" in the row to which the water is supplied to the crop. By following this procedure, for every acre inch of irrigation water used from the water supply only 85 percent will be available for use by the crop.

Requirements by Stage of Growth and Development

Large quantities of water must be supplied to satisfy the evapo-transpiration requirements of growing plants. Water requirements from various crops have been studied for a number of years at the Garden City, Kansas, Branch Experiment Station. Data from this research is used because it studied the timing of irrigations on crop yields. The small plot experiments were conducted by applying 6 inches of water at different stages of plant growth and different combinations of stages. The capacity to deliver the required amount of water was not a problem. The soil was relatively homogenous on the small plots.

The thirteen corn growing activities are summarized by Figure 4 plus the combination of irrigation timings are

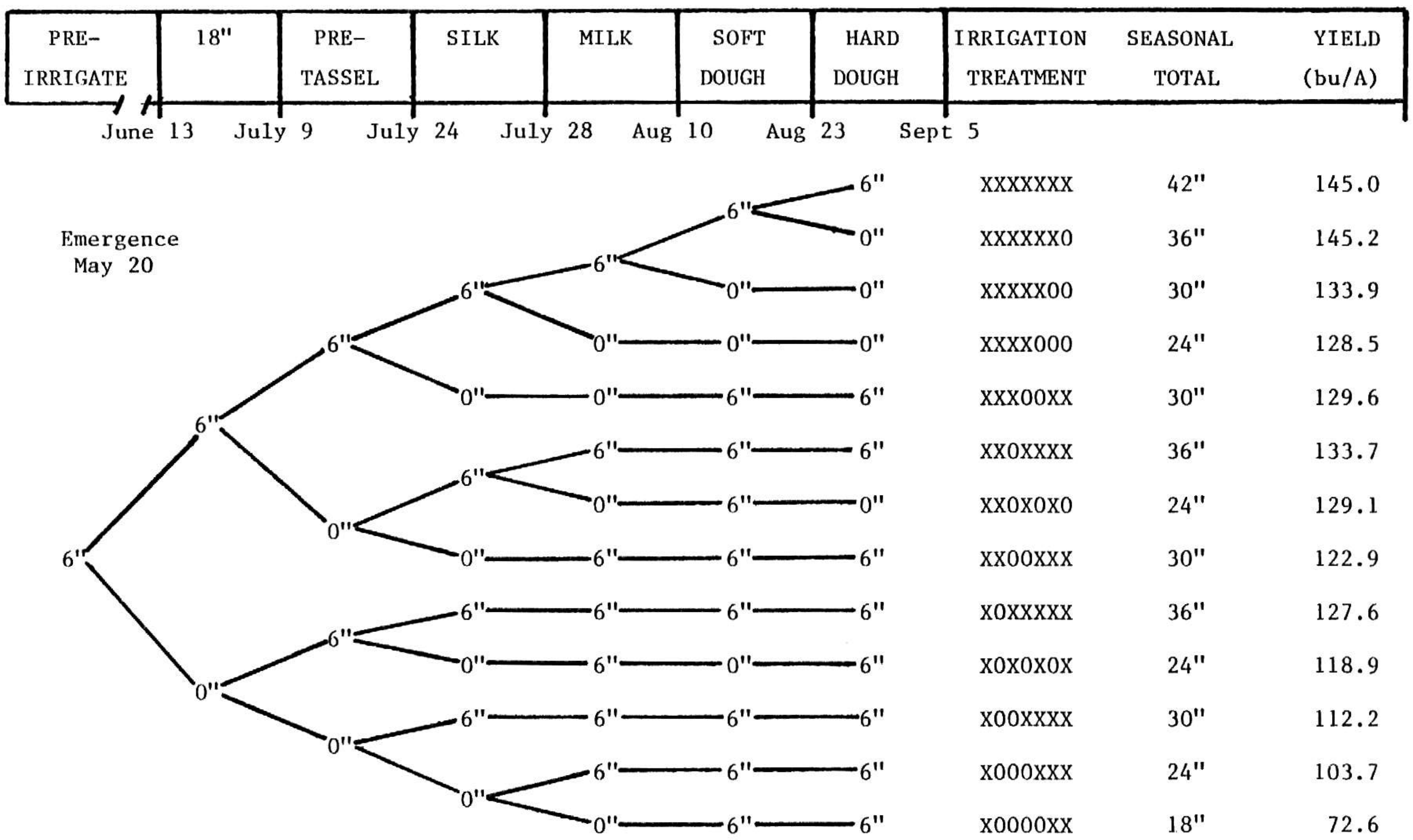

FIGURE 4. Consumptive use summary of corn yield response to irrigation, Garden City, Kansas, 1975-1976.

specified. Total irrigation water applied varies from 18 to 42 inches a year. This is in addition to the average rainfall received during the growing season of 7.5 inches. Although the experiments were ran on other years, the 1975 and 1976 crop years were selected as being representative of an average year with respect to rainfall by Mark Hooker, Research Agronomist at the Garden City Experiment Station. The 13 activities are identified in the model by a "C" followed by seven combinations of "X" or "O" depending on the stage when corn receives irrigation water. An "X" indicates six inches of irrigation water was applied while a "O" indicates no water was received during that period. The physiological stages used by the Garden City Experiment Station and the model are: 18", pre-tassel, silk, milk, soft dough, and hard dough.

The yields from the experiments varied from 72 to 145 bushels an acre depending on the irrigation treatment received. The reported yields were adjusted to 12.5 percent moisture by experiment station personnel.

Figure 5 summarizes the seven soybean growing activities used in the model. The activities are specified by the combinations of irrigation timings used on the soybean crop. Total irrigation water applied varies from 10 to 26 inches. The seven soybean growing activities are identified in the model by a "B" followed by six combinations of "X" or "O" depending on the chronological order the soybean growing activity received irrigation water. An "X" incicates

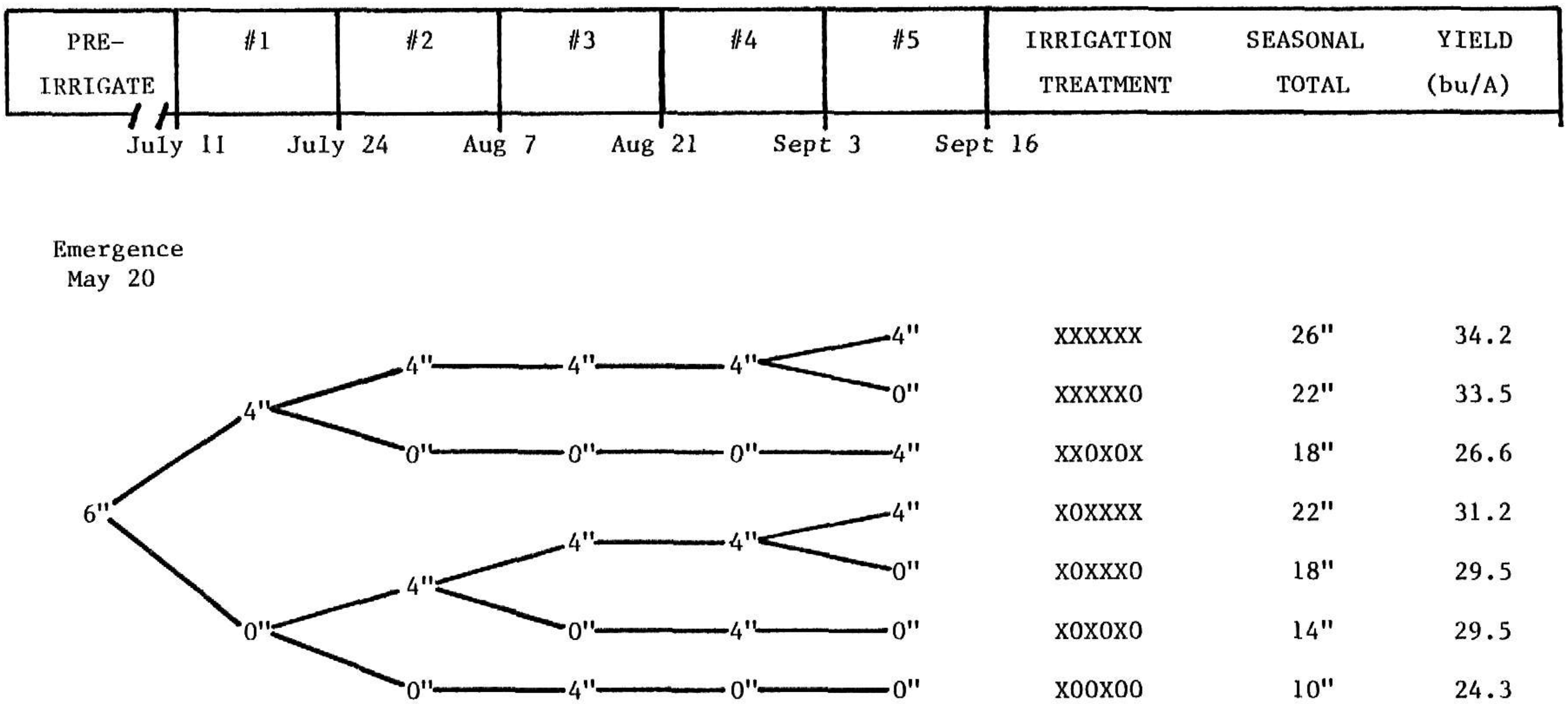

FIGURE 5. Consumptive use summary of soybeans yield response to irrigation, Garden City 1975-1976.

irrigation water was received while an "O" means no water was received.

Figure 6 summarizes the seven grain sorghum growing activities used in the model. The activities specify the combinations of irrigation timings used to apply 10 to 30 inches of irrigation water on the sorghum.

The six wheat activities are summarized by Figure 7. The activities specify the combinations of irrigation used in applying from 0 to 24 inches of irrigation water to the wheat crop. The six wheat growing activities are identified in the model by a "W" followed by five combinations of "X" or "O" depending on the chronological order the wheat growing activities received irrigation water. An "X" indicates irrigation water was received while the "O" indicates no water was received. The fallow-wheat growing activity is labeled "FALLOW". Physiological stages used by the Garden City Experiment Station and the model are: joint, boot, flowering, and milk.

Water Application Periods

The experimental plot which provided the data of crop yield and water applied was not constrained by well capacity or time available to apply the water. Plots were very small relative to well capacity in which case well capacity is no problem. However, most farmers are confronted with a well capacity which is limited relative to the amount of land. Thus, this model provided constraints on how much water could be pumped to meet the crops requirements at various

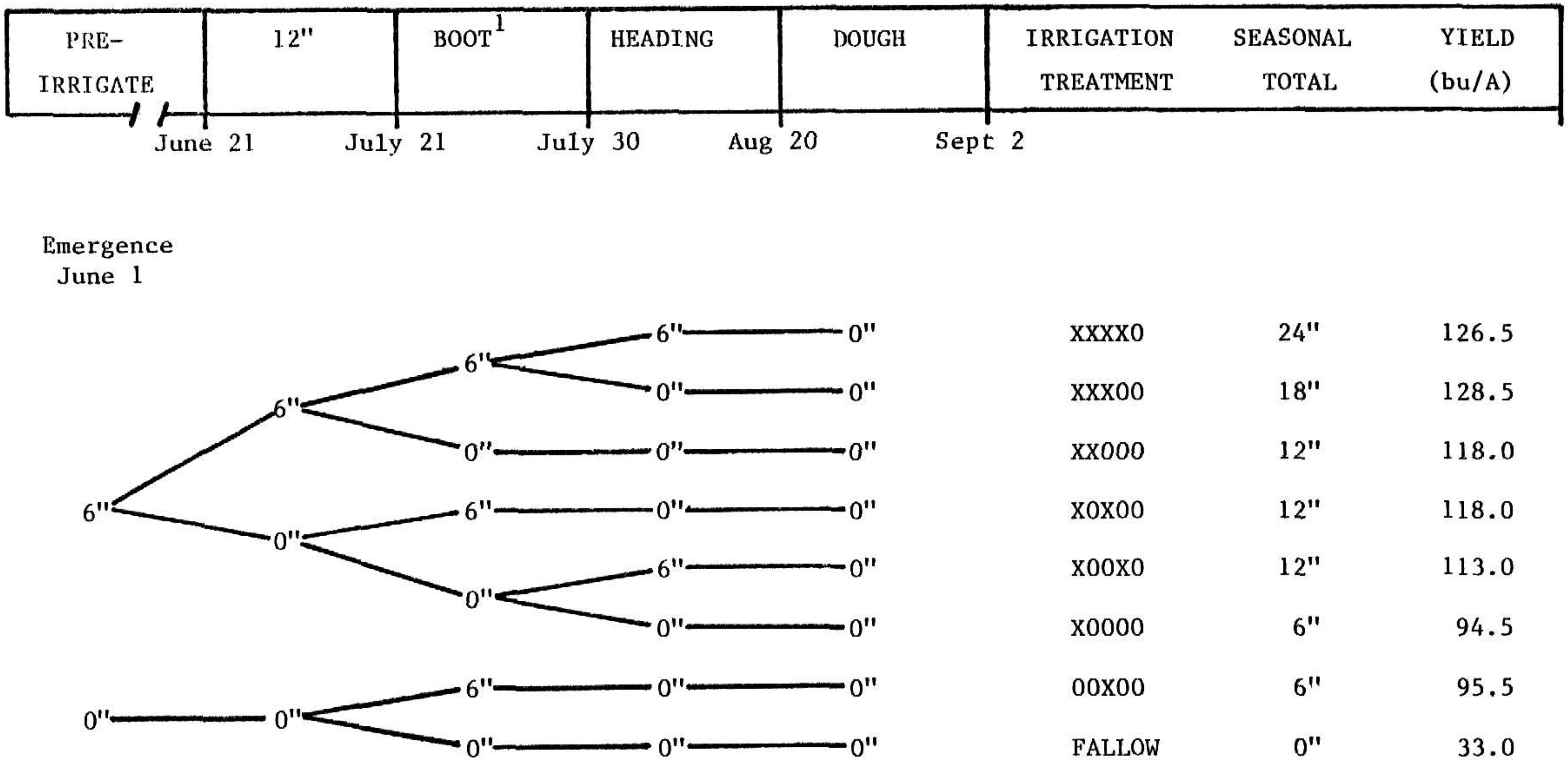

FIGURE 6. Consumptive use summary of Sorghum yield response to irrigation, Garden City, Kansas 1976-1978.

[1]Time of canopy closure should be noted usually occurs around this stage depending on the available soil moisture for growth and may be very fleeting under drought conditions.

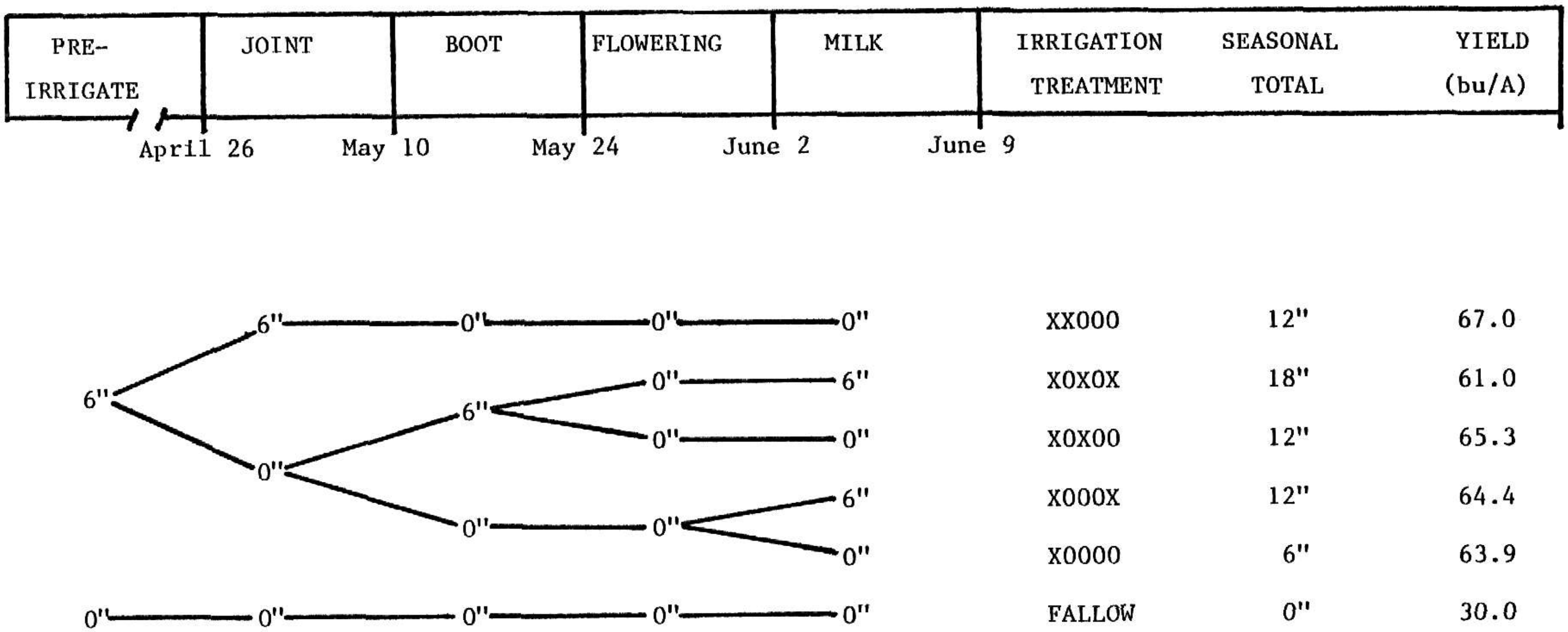

FIGURE 7. Consumptive use summary wheat yield response to irrigation, Garden City, Kansas 1975-1978.

stages. Figure 8 shows the classification of the pre-season and growing season into periods used in the model.

The periods used in the model are not results from the experiment on water application at various stages of growth. Studies by Brown (7) on wheat, Hanaway (17) on corn and soybeans and Vanderlip (42) on sorghum are used to identify these periods. The timing of the various periods will vary with the planting date as will the yields of the crops. Planting dates were assumed to be; corn-May 4, soybeans-June 1, sorghum-June 10, and wheat-September 20. These planting dates are the average dates used in the Garden City Station's experiment plot from which data is used.

There are 21 rows in the model's matrix used to represent the irrigation year, with these periods varying from 2 to 91 days in length (Figure 8). The irrigation water resource periods are labeled in the model by the month, beginning and ending day of the period they represent, or just a month's name if they contain the whole month. Physiological stages of the crops will occur during one, or a combination of several of these time periods. Due to the overlapping of physiological stages, it is necessary to use a series of transfer rows to link the irrigation water time period with physiological stages of the crops. The 21 transfer rows designed to irrigate during physiological stages are labeled after the crop and the period in that crops physiological stage they represent.

The model allows the pre-plant irrigation of corn to

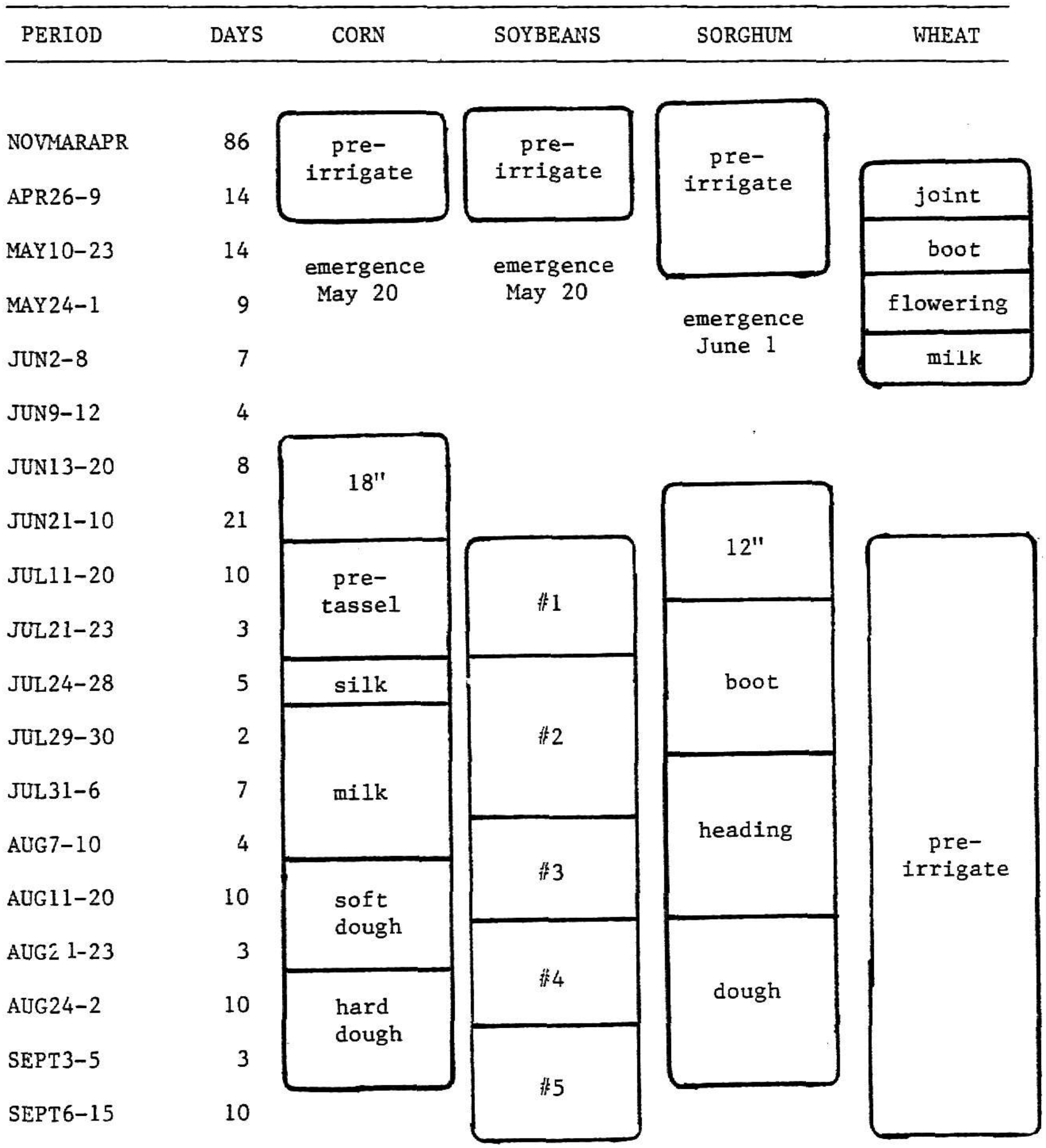

FIGURE 8. Comparitive physiological crop stages.

Source: Physiological Stages of Growth For Corn, Sorghum, Wheat, and Soybeans Compiled by Iwan D. Teare for Kansas Irrigators. KSU. (April 1 1977).

take place during October, November, March, and April. The 18" stage in the model is from June 7 through June 22 followed by the pre-tassel stage which lasts until July 8. These are not critical periods for the corn crop, so the model is somewhat lenient in specifing the periods. The critical silking stage is limited to just five days from July 9 to July 13. The milk stage is given 14 days from July 14 to July 26. The soft and hard dough stages are 15 day periods from July 27 to August 11 to August 24, respectively.

The model allowed pre-plant irrigation of soybeans in November and April 1 through May 28. Irrigation dates for soybeans were not identified by their phsiological stages in the experiment station's reports but rather by specified dates. These five periods are approximately 12 days long and start on July 9 and run through September 8. They are identified in the model by a "B" followed by the number (1-5) of the irrigation period.

The model allows the pre-plant irrigation of grain sorghum to take place during November, March 1 through June 5. The 12" stage in the model is from July 9 through July 27, an 18 day period. The boot stage is from August 5 through August 14, a 10 day period. The critical period of sorghum heading is limited to eight days from August 15 to August 22. The milk and dough stages are each given 10 days from August 23 to September 1 to September 11, respectively.

The model allows the pre-irrigation of wheat to take place from July 9 to September 12, a 66 day period. The 14 day joint and boot stages are from May 1 to May 14 to May 28, respectively. During May 29 to June 6 the wheat is in the flowering stage. The milk stage is from June 7 through June 13.

Well Yield

The draw down of the Ogallala acquifer has influenced well yield and consequently the most profitable crop mix is affected also. As well yield decreases to the level where an inadequate volume of water is available within the period constraint for applying water, farmers adjust the amount of water applied or select a crop more tolerant to moisture stress. The following equation shows the relationship between well yield (GPM) and the depth of the acquifer:

$$Q = \frac{P(H^2 - h^2)}{1055 \log R/r} \text{ [1]}$$

where

Q = well yield or pumping rate, in GPM

P = permeability of the water bearing sand, in gal/day/sq. ft.

H = satatuarated thickness of the aquifer before pumping, in ft.

h = depth of water in the well while pumping, in ft.

R = radius of the cone of depression, in ft.

r = radius of the well, in ft.

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[1] Ground Water and Wells, Johnson Division , VOP Inc., Saint Paul Minnesota, 55165, p. 104.

If the saturated thickness is reduced one-half, the value of (H^2-h^2) and GPM is reduced to one-fourth of the original value, assuming other variables remain unchanged and that h is 1/2 H. Differences in well yield caused by hydrological differences or by a decline in the water table result is large differences in water volume available in relatively short periods during critical plant stages. The model is used to show the effect of differences in well yield on farm income, crop acreages and timing of irrigation by changing the B coefficient of the water supply equation to consider 200, 400, 600, 800, 1000 to 1200 GPM.

Crop Budgets

Crop cost are reported in Tables B1 to B4 of Appendix B. Kansas State University farm management records were used to estimate the cost of raising crops with the exception of labor, fertilizer, and pumping cost. Pumping cost were adjusted to represent changes in the amount of water applied. The fertilizer costs estimates were based on yield per acre, and this relation is specified in Tables B1 to B4 of Appendix B. The other variable costs of growing crops remain the same for the different water and timing combinations for each crop.

Input prices are 1980 reported annual prices paid by Kansas farmers. A $3.00 per bushel price is used for corn. Prices of wheat, grain sorghum and soybeans are determined by a historical average of their price to the price of corn. This ratio multiplied by $3.00 determine the price of the commodity. The resulting price of wheat, grain sorghum and soybeans that were used are \$3.81, \$2.64, and \$7.23 respectively.

Irrigation pumping costs were estimated using an equation that related GPM to cost per acre. This equation was estimated from data generated by an irrigation "pump" simulation model (9). The equation included independent variables of water pumped (GPM), feet of lift (LIFT) the number of inches applied per acre (INCHES), and the cost of energy, in units of 1000 cubic ft. (ENCST). The dependent variable was variable cost per acre of operating an irrigation system (OPACRE). The equation was

$$\text{OPACRE} = -19.715523 - 0.003204\text{GPM} + 0.085746\text{LIFT} + 1.065039\text{INCHES} + 6.792890\text{ENCST}$$

In the model for the pumping activities, a value of 1.065 is placed in the objective row as the cost of pumping one acre inch. The other variable cost, GPM, LIFT and ENCST, are not included in the pump activities but as part of the crop cost per acre. These costs are adjusted for each change in GPM. The energy cost is \$2.00/ft^2 (natural gas) and the lift is 200 ft. for all model runs.

Chapter IV

Model and Results

Six computer runs were made with the results summarized in Table 1. For each run the well yield was changed which resulted in changes in the objective function value and the combination of crops, amount of water applied and timing of application. The objective function is the maximum obtainable given the constraint on land and water available by period.

The objective function value is gross receipts less variable costs. It is assumed the land ownership costs and machinery depreciation costs remain fixed.

Influence of GPM on Objective Value

As well yield increases in terms of GPM, the objective value increases because more water is available to increase crop production. To increase crop production the model selects crops or water application that allow higher yields per acre.

With only 200 GPM capacity available, water is the most limiting resource and the model selects the combination of crops and water application alternative that provides the highest return to water. As GPM increases to 1200, land gradually becomes the more limiting resource. Thus at 1200, the model selects the activities that provide the highest return per acre. The value of an acre of land is reported in Table 1. (The shadow price of land is an imputted value to land by the model determined by the reduction of the

TABLE 1

MODEL RESULTS REGARDING THE OBJECTIVE VALUE, ACRES AND WATER APPLIED FOR DIFFERENT WATER APPLICATION RATES

ITEM	200 GPM	400 GPM	600 GPM	800 GPM	1000 GPM	1200 GPM
Net Income	$25,747	$28,735	$29,806	$30,706	$31,554	$32,403
Marginal Value one Acre	124	163	171	173	174	175
Corn Acres						
XXXXXXO	0	15.02	22.52	30.03	37.54	45.05
XXXOOXX	0	19.17	35.98	48.02	60.07	72.11
Sorghum Acres						
XXXOO	0	10.17	9.06	12.04	15.01	17.99
XXOOO	46.61	42.07	29.38	0	0	0
XOXOO	15.02	0	0	0	0	0
XOOOO	27.82	0	0	0	0	0
Wheat Acres						
XXOOO	20.97	42.07	0	69.90	47.38	24.85
XOOOO	49.58	30.80	63.04	0	0	0

objective function of one acre less were used.) This shadow price is an estimated annual value. Capitalizing the annual value provides an estimate of the market value of this land. The estimate price is higher than the market price for irrigation land partly because the capitalization formula assumes the annual value extends into perpetuity, whereas farmers realize the aquifer has limited life and the annual value will likely decline when the water is exhausted. If the model could acquire land for an annual cost of less than $124 per acre with a 200 GPM well to $175 per acre with a 1200 GPM well then additional land would be purchased and the land constraint would not be limiting the size of the unit.

Influence of Well Yield on Acres and Water Application

With an irrigation well producing 1200 GPM the 160 acre field has an objective value of $32,403, with a $175.23 shadow price per acre of cropland (Table 1). This income is from producing 15,886.5 bushels of corn, 2,311.93 bushels of sorghum, and 1,664.95 bushels of wheat. Corn production is from 45.05 acres using the XXXOOXX irrigation plan and 72.11 acres using the XXXOOXX irrigation plan. Grain sorghum production is from 17.99 acres using the XXXOO irrigation plan. Wheat production is from 24.85 acres using the XXOOO plan. All available irrigation water was used during June 13-20, July 11-30, August 7-23, and September 3-5. The shadow price of an acre inch of water varied from $0 to $6.94, with the highest value placed on water during the five day silking stage for corn.

With an irrigation well producing 1000 GPM, the 160 acre field has an objective value of $31,554, with a shadow price of an acre of cropland at $174.48. This income is from producing 13,235.69 bushels of corn, 1,929.64 bushels of sorghum and 3,174.13 bushels of wheat. Corn production is from 37.54 acres using the XXXXXXO irrigation plan and 60.07 acres using the XXXOOXX irrigation plan. Grain sorghum production is from using the XXXOO irrigation plan Wheat production is from the XXOOO irrigation plan used on 47.38 acres. All available irrigation water is used during June 13-20, and July 11-August 23. The shadow price of an acre inch of water varied from $0 to $6.94, with the highest value placed on water during the five day silking stage for corn.

A 160 acre field with a well producing 800 GPM has an objective value of $30,706. This income is from producing 10,584.88 bushels of corn, 1,547.35 bushels of sorghum and 4,683.3 bushels of wheat. Corn production is from 30.03 acres using the XXXXXXO irrigation plan and 48.03 acres using the XXXOOXX irrigation plan. Grain sorghum production is from using the XXXOO irrigation plan. Wheat production is from 69.9 acres using the XXOOO irrigation plan. All available irrigation water is used during June 13-20, July 11-30, August 11-23, and September 6-15. The shadow price of an acre inch of water varied from $0 to $6.94, with the highest value placed on water during the five day silking stage for corn.

With an irrigation well producing 600 GPM the 160 acre field has an objective value of $29,806, with a shadow price of an acre of cropland at $171.20. This income is from producing 7,934.07 bushels of corn, 4,632.3 bushels of sorghum and 4,223.79 bushels of wheat. Corn production is from 22.52 acres using the XXXXXXO irrigation plan and 35.98 acres using the XXXOOXX irrigation plan. Grain sorghum production is from 9.07 acres using the XXXOO irrigation plan and 29.38 acres using the XXOOO irrigation plan. Wheat production is from XXOOO irrigation plan used on 63.04 acres. The shadow price of an acre inch of water varied from $0 to $6.94 with the highest value placed on water during the five day silking stage of corn.

With an irrigation well producing 400 GPM, the 160 acre field has an objective value of $28,735, with a shadow price of an acre of cropland of $163.39. The production of 4,664.42 bushels of corn, 6,361.22 bushels of sorghum, and 4,777.91 bushels of wheat generates this income. Corn production is from 15.02 acres with an XXXXXXO irrigation plan. Grain sorghum production is from 10.87 acres with an XXXOO irrigation plan and 42.08 acres with an XXOOO irrigation plan. Wheat production is from 42.08 acres with an XXOOO irrigation plan and 30.8 acres with an XOOOO irrigation plan. All available irrigation water is used from April 26-May 23 and from June 13-September 15. The shadow price of an acre inch of water varied from $0 to $6.94, with the highest value placed during the corn silking stage.

A 160 acre field with a well producing 200 GPM has an objective value of $24,747 from producing 9,901.21 bushels of sorghum and 4,558.27 bushels of wheat, with a shadow price of an acre of cropland of 4124.43. Grain sorghum production is from the XXOOO, XOXOO, and XOOOO irrigation plans on 46.61, 15.02, and 27.83 acres, respectively. Wheat production is from 20.97 and 49.58 acres using the XXOOO and XOOOO irrigtion plan, respectively. All available irrigation water is used from April 26-May 23 and June 21-September 15. The shadow price of an acre inch of water varies from $0 to $8.79, with the high value placed during sorghums 12" and boot stages.

From these results several observations follow. With adequate water available, corn tends to be the crop selected by the model, but of the 13 possible irrigation activities for corn only two full irrigation activities were used. When water became limited, the acres of corn were replaced by nearly equal amounts of wheat and sorghum acres. As water became very limited no corn was chosen and the acres of wheat and sorghum were of a limited irrigation plan. At no time did the model select a soybean activity, but full irrigated soybeans had an opportunity cost of zero associated with it in the model indicating they were very close to being selected.

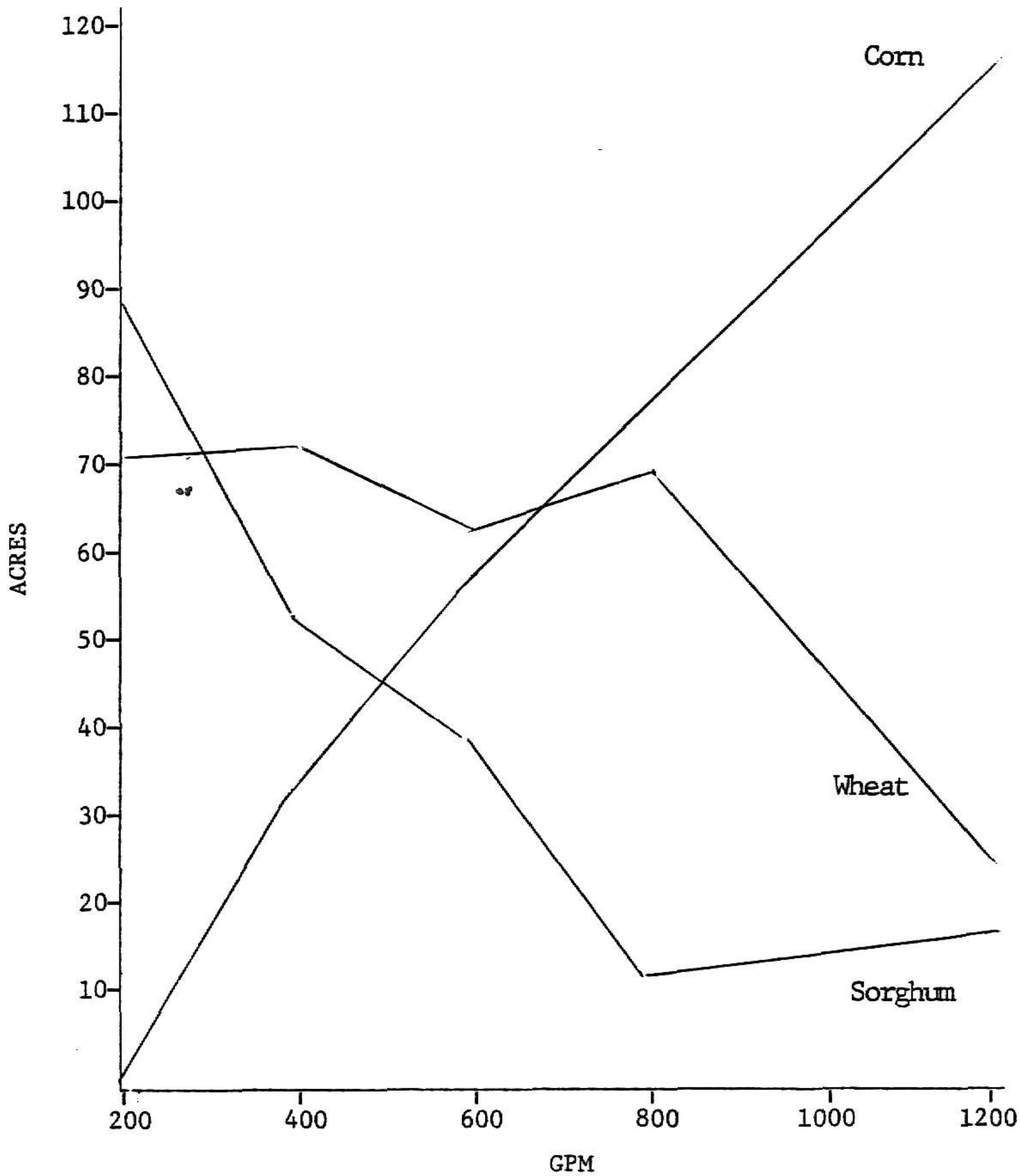

Figure 9. Optimum crop combination for 160 acres given water restraints.

CHAPTER V

SENSITIVITY ANALYSES

Purpose of Sensitivity Analysis

The linear programming model is developed to determine the most profitable crop mix and irrigation practice to be used on the crops selected for the 160 acres. Given a set of input and output prices along with resource levels, the model generates the correct crop combinations that will maximize income as reported in Chapter IV.

The process of studying the effects on the most profitable plan of changing some parameter in the linear programming model is called sensitivity analysis. The results reported in Chapter IV shows the models sensitivity to changes in GPM. In this chapter, sensitivity analysis will consider changes in prices of products, and the value of water at various periods.

Results of Sensitivity Analysis

A single price was placed on the grain produced by the farm model. In a linear program such as this, the important consideration is not the level of prices given to inputs and output, but the relative relationship among them. In calculating the prices of the crops, the last eight years of prices, as published by the Kansas Crop and Livestock Reporting Service, were used to find an average price. The resulting average prices were adjusted to current prices by first assigning the current price to corn. Prices for the other crops were then established by multipling the price of corn by the eight year average price of the crop, then dividing the product by the eight year average price of corn.

Figure 10 shows the range of price changes possible for the crops at the six GPM ratings that could occur before there would be a change in the optimum combination of crops selected by the model. At a 600 GPM rating, the range becomes very narrow for sorghum and wheat, but somewhat larger for corn. The price range for corn is relatvely stable throughout most of the GPM ratings. The opposite holds for wheat and sorghum. Wheat has the largest range until GPM decreases to less than the 800 when the upper limit on price decreases to approximately $.15 of the lower price. The upper price limit for wheat is fairly consistent throughout the lower range, while the lower price limit is decreasing as GPM's decreases. Grain sorghum shows a situation almost opposite wheat with the upper and lower price limit increasing at the lower GPM ratings. Since soybeans did not enter the model's solutions they are not represented in this graph.

Figure 10 shows that the most profitable mix is affected by corn price changes much the same regardless of the GPM. This illustrates again that water availability is the most important consideration for corn; whereas, for wheat and grain sorghum, the price range is very small for some GPM's. This means that small changes in price can result in changes in the most profitable plan. Returns to

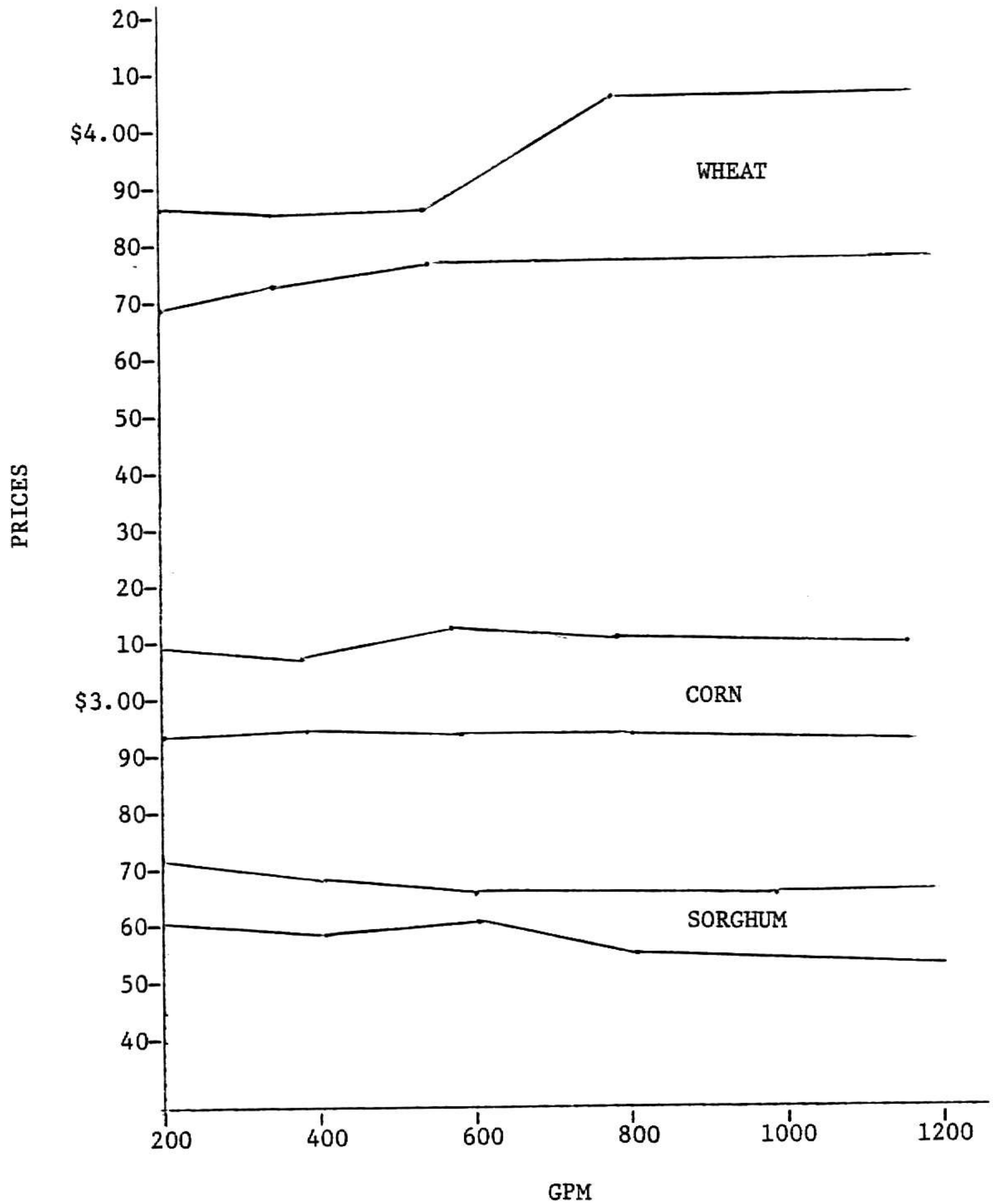

FIGURE 10. Price ranges possible before changes would occur in the solution.

wheat and grain sorghum are very close and competitive at 600 GPM.

Table 2 summarizes the dollar losses that would be incurred by the model if an additional acre of land were to be used for the specified activity. The first column is a list of the four crops and the irrigation practice used. The first letter in the variables' name indicates the crop; corn = "C", sorghum = "S", soybeans = "B", wheat = "W". The following letters in the variables, "X" and "O", indicate an irrigation period with the "X" indicating the crop receiving the irrigtion water and "O" indicating the crop did not receive the irrigation water. The following columns are the opportunity cost should the crop be substituted for one in the most profitable solution.

Table 3 and 4 show the value an additional acre inch of water would add to the model should it be available at calendar periods and physiological crop periods, respectively. Table 3 is divided into the same calendar periods as the model. These calendar periods were selected because of physiological crop stages which occurred on these dates.

In Table 4, the physiological stages of the crops are represented. The negative values indicate that an additional inch of water would have reduced the objective. In Table 3, this negative value can not be greater than $1.065 because that was the cost of pumping an additional acre in. However, in Table 4, the model takes into account other considerations; therefore, the negative value (cost) can be

TABLE 2

THE OPPORTUNITY COST OF PRODUCING ONE ACRE OF THE CROP ACTIVITY BY GPM

CROP/IRR.	200 GPM	400 GPM	600 GPM	800 GPM	1000 GPM	1200 GPM
CXXXXXXX	$29.30	$11.51	$ 8.12	$ 8.12	$ 8.12	$ 8.12
CXXXXXXO	18.95	-	-	-	-	-
CXXXXXOO	9.75	19.25	17.08	15.86	15.86	15.86
CXXXXOOO	5.21	22.85	24.08	22.85	22.85	22.85
CXXXOOXX	15.01	9.09	10.04	15.86	15.86	15.86
CXXOXXXX	11.89	17.33	12.71	15.71	15.71	15.71
CXXOXOXO	.19	7.88	10.04	13.04	13.04	13.04
CXXOOXXX	39.36	4.62	1.23	2.99	2.99	2.99
CXOXXXXX	58.55	32.53	39.59	39.59	39.59	39.59
CXOXOXOX	.19	12.72	14.23	12.99	12.99	12.99
CXOOXXXX	60.62	59.00	61.44	64.44	64.44	64.44
CXOOOXXX	42.35	39.91	42.35	45.35	45.35	45.35
CXOOOOXX	112.25	113.41	119.24	122.24	122.24	122.24
MXXXXO	74.31	7.67	4.60	4.60	4.60	4.60
MXXXOO	28.44	3.08	1.23	2.99	2.99	2.99
MXXOOO	-	4.88	1.77	1.77	1.77	1.77
MXOXOO	-	9.76	16.82	16.82	16.82	16.82
MXOOXO	7.84	7.84	3.99	5.76	5.76	5.76
MXOOOO	11.97	38.20	45.26	47.03	47.03	47.03
MOOXOO	43.11	52.88	59.93	59.93	59.93	59.93
MFALLOW	224.87	302.79	318.41	323.46	324.97	326.48
BXXXXXX	13.50	4.55	4.09	5.86	5.86	5.86
BXXXXXO	5.06	5.06	5.14	5.18	5.18	5.18
BXXOXOX	42.98	54.95	55.86	56.25	56.25	56.25
BXOXXXX	20.77	21.69	22.05	22.20	22.20	22.20
BXOXXXO	12.29	33.98	34.54	34.79	34.79	34.79
BXOXOXO	12.29	33.98	34.54	34.79	34.79	34.79
BXOOXOO	37.92	71.58	72.27	73.27	73.27	73.27
WXXOOO	-	-	-	1.04	1.04	1.04
WXOXOX	15.51	15.51	15.51	15.51	15.51	15.51
WXOXOO	1.04	1.04	4.71	6.48	6.48	6.48
WXOOOX	3.43	3.43	3.43	3.43	3.43	3.43
WXOOOO	3.67	2.97	3.67	5.44	5.44	5.44
WFALLOW	164.52	242.44	258.06	263.11	264.62	266.12

TABLE 3

SHADOW PRICES OF AN ACRE INCH OF WATER AT SPECIFIED TIMES BY GPM

DATE	200 GPM	400 GPM	600 GPM	800 GPM	1000 GPM	1200 GPM
Nov-Mar-Apr	-	-	-	-	-	-
Apr 26-9	.77	.77	.25	-	-.25	-
May 10-23	-	-	-.25	-.25	-.25	-
May 24-1	-	-	-	-	-	-
Jun 2-8	-1.065	-1.065	-1.065	-1.065	-1.065	-1.065
Jun 9-12	-	-	-	-	-	-
Jun 13-20	-1.065	.99	-	-	-	-
Jun 21-10	6.41	.99	-	-	-	-
Jul 11-20	6.41	2.38	2.56	2.13	2.13	2.13
Jul 21-23	6.41	2.38	2.56	2.13	2.13	2.13
Jul 24-28	6.41	4.83	4.83	4.83	4.83	4.83
Jul 29-30	6.41	2.38	2.38	2.13	2.13	2.13
Jul 31-6	5.89	.48	-	-	-	-
Aug 7-10	5.89	.48	-	-	-	-
Aug 11-20	5.89	.48	.79	.96	.96	.96
Aug 21-23	5.89	.48	.79	.96	.96	.96
Aug 24-2	5.89	.48	-	-	-	-
Sept 3-5	5.89	.48	-	-	-	-
Sept 6-15	5.89	.48	-	-	-	-

TABLE 4

SHADOW PRICES OF AN ACRE INCH OF WATER DURING CROP PERIODS BY GPM

CROP PERIOD	200 GPM	400 GPM	600 GPM	800 GPM	1000 GPM	1200 GPM
C-pre	1.25	1.25	1.25	1.25	1.25	1.25
C-18	1.25	2.43	1.25	1.25	1.25	1.25
C-pre-T	7.93	4.06	4.26	3.76	3.76	3.76
C-silk	6.80	6.94	6.94	6.94	6.94	6.94
C-milk	2.42	1.82	1.25	1.25	1.25	1.25
C-SD	8.19	1.82	2.18	2.38	2.38	2.38
C-HD	1.62	1.82	1.25	1.25	1.25	1.25
B-pre	1.25	.49	- .68	- .98	- .98	- .98
B-1	5.42	-1.14	-1.02	-1.46	-1.46	-1.46
B-2	2.99	-1.14	-1.02	-1.46	-1.46	-1.46
B-3	-5.19	-1.14	-1.02	-1.46	-1.46	-1.46
B-4	-5.19	-1.14	-1.02	-1.46	-1.46	-1.46
B-5	-5.19	-1.14	-1.02	-1.46	-1.46	-1.46
GS-pre	1.25	1.25	1.25	1.25	1.25	1.25
GS-12	8.80	2.34	1.25	1.25	1.25	1.25
GS-boot	8.80	4.06	4.06	3.76	3.76	3.76
GS-head	6.88	.51	- .67	- .77	- .77	- .77
W-pre	8.19	1.82	1.25	1.25	1.25	1.25
W-joint	2.16	2.16	1.55	1.25	1.25	1.25
W-boot	1.08	1.08	.47	.17	.17	.17
W-milk	-2.58	-2.58	-2.58	-2.58	-2.58	-2.58

greater than $1.065.

The highest shadow prices occur when water is most limiting - at 200 GPM (Table 3). Also, at low GPM's, shadow prices occur during all periods in the summer season. The seasons represent the growth and reproductive stages. As GPM increases, the number of periods with a shadow price and the magnitude of the shadow price decreases.

The highest value to water with 200 GPM occurs with grain sorghum during the boot and 12" stage. Value of an acre inch of water during corn soft dough stage is nearly as high as the high value for grain sorghum. Corn in soft dough and pre-season irrigation of wheat compete for water as they both occur at the same time; consequently they have the same shadow price.

As the GPM increases, the value of the shadow prices decrease and the number of negative values increase. A negative value for a shadow price implies sufficient water is available and any additional would not increase but decrease the objective.

CHAPTER VI

Conclusions and Implications

Increased pumping cost caused by a combination of increased pumping depth and higher fuel cost in western Kansas have caused a fundamental change to the cost structure of irrigation in the area. This problem is compounded by the decreasing output of many wells.

Linear programming is used to calculate the most profitable crop and irrigation plan for a southwesten Kansas 160 acre field when given six different irrigation well capacities in an attempt to maximize profit for the model farm. On a 160 acres, a well with 1200 GPM has the capacity to fully irrigate 117 acres corn. With a 1400 GPM capacity well, nearly 160 acres would be planted corn.

Objective function value increases from $25,747 to $32,403 as GPM increases from 200 to 1200 on 160 acres. This increase is the result of more water available and selecting crops with higher returns per acre.

Corn acres planted increases from zero to 117 acres as GPM increases from 200 to 1200. Grain sorghum acreage decreases from 89 to 18 as GPM increases from 200 to 1200 on 160 acres. Wheat acreage decreases from 71 to 25 as GPM increases from 200 to 1200.

As GPM increases from 200 to 1200, grain sorghum and wheat acreage is replaced by corn. Grain sorghum and wheat give a higher return to a limited amount of water. As water becomes less limiting relative to land, corn replaces grain sorghum and wheat. When land is the most limiting resource, the model selects fully irrigated corn because corn provided a higher return to land.

At all levels of GPM studied, forcing the model to produce corn with limited irrigation results in the largest reduction in the objective function value. The reduction in objective function value is larger for higher GPM's for grain sorghum or wheat than low GPM's.

For all levels of GPM studied, water was limiting from July 11 through 30 and August 11 through 23. The July period is the critical stage of the corn and grain sorghum growth, reproductive and maturation stages. The August period is when wheat is irrigated in preparation for planting. For 200 and 400 GPM, water is limiting from June 13 through September 15.

The highest shadow price for water occurs for the corn silking stage with GPM of 400 or greater. With 200 GPM, grain sorghum during the 12" and boot phase provides the highest return to water. Water during the corn silk stage has a value of $6.94 per acre inch or over $83.00 per acre foot (for 400 GPM or larger). The shadow price of water was higher in the July 24-28 period with a value of $4.83 to $6.41 per acre inch. The shadow price of water is the highest during the corn silking stage with a value of $6.80-$6.94 per acre inch.

As the supply of water available for irrigation becomes more limiting, the decrease in revenues caused by the limited water available for crops can be partially offset by raising a combination of crops that are the most responsive to the water when it is available; consequently maintaining profits at levels near those when water is not so limiting. As the supply of irrigation water decreases to the point where there is not enough water available for full irrigation of the most responsive crop, rather than limit the total irrigated acres, the available water is applied to the total developed area during combinations of critical periods of crops most responsive to the water.

After a review of the linear programming model results for the various sensitivity analyses, several recommendations can be made to farmers producing crops under irrigtion in southwestern Kansas. The primary determinant of what crop to plant is the irrigation well capacity. In general, to maximize income the farmer should plant as much corn as possible that can be grown without having to allow the crop to experience an ET deficit. For all well outputs of 400 GPM and above for 160 acres, corn proves to be the most responsive crop to water in the model if it is not put in a stress situation. At the higher GPM ratings, nearly equal acres of full irrigated sorghum and wheat are recommended by the model for acres left when there is not adequate water for full irrigation of corn. As irrigation water becomes very limiting, rather than recommend a combination of fully irrigated crops and a Crop-Fallow system, the model selects the limited irrigated sorghum and wheat alternatives in nearly equal acres.

Limitations of This Study

Several factors and alternatives may affect or limit the applicability of the conclusions derived from this study. The first is that the linear programming model is structured to look at only the direct effects of irrigation to crops. There are secondary effects that were not considered. For instance, adequate labor was assumed to be available with no restraints on timing. This is not the case on the farm level. When labor is available may be an important variable in the selection of a crop by the farmer. What machinery the farmer has access to may also effect what crop the farmer selects to grow. Wheat will require a different type of machine for planting than the row crops. Corn requires a special attachment on a combine for harvesting.

A second factor is that the linear programming model has only one date to select for a planting date. This date was picked because of its consistency with the planting dates used by the Garden City Experiment Station from which the data on crop yield was used. No data was available on penalities that would be incurred should these dates be moved. For this reason, and because of the complexity that would be involved in building a model with multiple planting dates, the planting date was limited to a single date.

This model is based on data taken from years considered normal. The weather in this area has a tendency to have wide year to year fluctuations. New frontiers could be opened if the risk assumed by years not considered normal would be taken into account.

Another factor not considered by the model is the quantity of water applied at an irrigation is always six inches except for soybeans which receive four inches. Although only a minority of farmers in the area have sprinkler systems, these farmers have the option of applying smaller quantities of water in a single irrigation. Thus, these farmers can apply irrigation water to a larger number of acres during critical crop periods. This is a fundamental situation not taken into account by the model.

The possibilities of future studies to expand this type of model exist. These studies will be limited by more and better data needed on which to base the models.

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APPENDIX

Appendix A

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NAME
ROWS
 N  Z
 L  CORN
 L  BEANS
 L  MILO
 L  WHEAT
 L  CROPLAND
 L  PUMPOP
 L  DRYING
 L  INTEREST
 L  N-FERT
 L  P20
 L  C-PRE
 L  C-18
 L  C-PRE-T
 L  C-SILK
 L  C-MILK
 L  C-SD
 L  C-HD
 L  B-PRE
 L  B-1
 L  B-2
 L  B-3
 L  B-4
 L  B-5
 L  GS-PRE
 L  GS-12
 L  GS-BOOT
 L  GS-HEAD
 L  W-PRE
 L  W-JOINT
 L  W-BOOT
 L  W-MILK
 L  NOVMARAP
 L  APR26-9
 L  MAY10-23
 L  MAY24-1
 L  JUN2-8
 L  JUN9-12
 L  JUN13-20
 L  JUN21-10
 L  JUL11-20
 L  JUL21-23
 L  JUL24-28
 L  JUL29-30
 L  JUL31-6
 L  AUG7-10
 L  AUG11-20
 L  AUG21-23
 L  AUG24-2
 L  SEP3-5
 L  SEP6-15
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COLUMNS
 LC11      Z          -     1.06500    C-PRE     -      .85000
 LC11      NOVMARAP         1.00000
 LC12      Z          -     1.06500    C-PRE     -      .85000
 LC12      APR26-9          1.00000
 LC21      Z          -     1.06500    C-18      -      .85000
 LC21      JUN13-20         1.00000
 LC22      Z          -     1.06500    C-18      -      .85000
 LC22      JUN21-10         1.00000
 LC31      Z          -     1.06500    C-PRE-T   -      .85000
 LC31      JUL11-20         1.00000
 LC32      Z          -     1.06500    C-PRE-T   -      .85000
 LC32      JUL21-23         1.00000
 LC41      Z          -     1.06500    C-SILK    -      .85000
 LC41      JUL24-28         1.00000
 LC51      Z          -     1.06500    C-MILK    -      .85000
 LC51      JUL29-30         1.00000
 LC52      Z          -     1.06500    C-MILK    -      .85000
 LC52      JUL31-6          1.00000
 LC53      Z          -     1.06500    C-MILK    -      .85000
 LC53      AUG7-10          1.00000
 LC61      Z          -     1.06500    C-SD      -      .85000
 LC61      AUG11-20         1.00000
 LC62      Z          -     1.06500    C-SD      -      .85000
 LC62      AUG21-23         1.00000
 LC71      Z          -     1.06500    C-HD      -      .85000
 LC71      AUG24-2          1.00000
 LC72      Z          -     1.06500    C-HD      -      .85000
 LC72      SEP3-5           1.00000
 LB11      Z          -     1.06500    B-PRE     -      .85000
 LB11      NOVMARAP         1.00000
 LB12      Z          -     1.06500    B-PRE     -      .85000
 LB12      APR26-9          1.00000
 LB21      Z          -     1.06500    B-1       -      .85000
 LB21      JUL11-20         1.00000
 LB22      Z          -     1.06500    B-1       -      .85000
 LB22      JUL21-23         1.00000
 LB31      Z          -     1.06500    B-2       -      .85000
 LB31      JUL24-28         1.00000
 LB32      Z          -     1.06500    B-2       -      .85000
 LB32      JUL29-30         1.00000
 LB33      Z          -     1.06500    B-2       -      .85000
 LB33      JUL31-6          1.00000
 LB41      Z          -     1.06500    B-3       -      .85000
 LB41      AUG7-10          1.00000
 LB42      Z          -     1.06500    B-3       -      .85000
 LB42      AUG11-20         1.00000
 LB51      Z          -     1.06500    B-4       -      .85000
 LB51      AUG21-23         1.00000
 LB52      Z          -     1.06500    B-4       -      .85000
 LB52      AUG24-2          1.00000
 LB61      Z          -     1.06500    B-5       -      .85000
 LB61      SEP3-5           1.00000
 LB62      Z          -     1.06500    B-5       -      .85000
 LB62      SEP3-5           1.00000
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LM11	Z	-	1.06500	GS-PRE	-	.85000
LM11	NOVMARAP		1.00000			
LM12	Z	-	1.06500	GS-PRE	-	.85000
LM12	APR26-9		1.00000			
LM13	Z	-	1.06500	GS-PRE	-	.85000
LM13	MAY10-23		1.00000			
LM21	Z	-	1.06500	GS-12	-	.85000
LM21	JUN21-10		1.00000			
LM22	Z	-	1.06500	GS-12	-	.85000
LM22	JUL11-20		1.00000			
LM31	Z	-	1.06500	GS-BOOT	-	.85000
LM31	JUL21-23		1.00000			
LM32	Z	-	1.06500	GS-BOOT	-	.85000
LM32	JUL24-28		1.00000			
LM33	Z	-	1.06500	GS-BOOT	-	.85000
LM33	JUL29-30		1.00000			
LM41	Z	-	1.06500	GS-HEAD	-	.85000
LM41	JUL31-6		1.00000			
LM42	Z	-	1.06500	GS-HEAD	-	.85000
LM42	AUG7-10		1.00000			
LM43	Z	-	1.06500	GS-HEAD	-	.85000
LM43	AUG11-20		1.00000			
LW11	Z	-	1.06500	W-JOINT	-	.85000
LW11	APR26-9		1.00000			
LW21	Z	-	1.06500	W-BOOT	-	.85000
LW21	MAY10-23		1.00000			
LW31	Z	-	1.06500	W-MILK	-	.85000
LW31	JUN2-8		1.00000			
LW51	Z	-	1.06500	W-PRE	-	.85000
LW51	JUL11-20		1.00000			
LW52	Z	-	1.06500	W-PRE	-	.85000
LW52	JUL21-23		1.00000			
LW53	Z	-	1.06500	W-PRE	-	.85000
LW53	JUL24-28		1.00000			
LW54	Z	-	1.06500	W-PRE	-	.85000
LW54	JUL29-30		1.00000			
LW55	Z	-	1.06500	W-PRE	-	.85000
LW55	JUL31-6		1.00000			
LW56	Z	-	1.06500	W-PRE	-	.85000
LW56	AUG7-10		1.00000			
LW57	Z	-	1.06500	W-PRE	-	.85000
LW57	AUG11-20		1.00000			
LW58	Z	-	1.06500	W-PRE	-	.85000
LW58	AUG21-23		1.00000			
LW59	Z	-	1.06500	W-PRE	-	.85000
LW59	AUG24-2		1.00000			
LW60	Z	-	1.06500	W-PRE	-	.85000
LW60	SEP3-5		1.00000			
LW61	Z	-	1.06500	W-PRE	-	.85000
LW61	SEP6-15		1.00000			
CXXXXXXX	Z	-	94.70000	CORN	-	145.00000
CXXXXXXX	CROPLAND		1.00000	PUMPOP		1.00000
CXXXXXXX	DRYING		145.00000	INTEREST		127.00000
CXXXXXXX	N-FERT		158.00000	P20		30.00000

CXXXXXXX	C-PRE		6.00000	C-18		6.00000
CXXXXXXX	C-PRE-T		6.00000	C-SILK		6.00000
CXXXXXXX	C-MILK		6.00000	C-SD		6.00000
CXXXXXXX	C-HD		6.00000			
CXXXXXXO	Z	-	94.70000	CORN	-	145.20000
CXXXXXXO	CROPLAND		1.00000	PUMPOP		1.00000
CXXXXXXO	DRYING		145.00000	INTEREST		127.00000
CXXXXXXO	N-FERT		158.00000	P20		30.00000
CXXXXXXO	C-PRE		6.00000	C-18		6.00000
CXXXXXXO	C-PRE-T		6.00000	C-SILK		6.00000
CXXXXXXO	C-MILK		6.00000	C-SD		6.00000
CXXXXXOO	Z	-	94.70000	CORN	-	133.90000
CXXXXXOO	CROPLAND		1.00000	PUMPOP		1.00000
CXXXXXOO	DRYING		133.00000	INTEREST		125.00000
CXXXXXOO	N-FERT		143.00000	P20		30.00000
Cxxxxxoo	C-PRE		6.00000	C-18		6.00000
CXXXXXOO	C-PRE-T		6.00000	C-SILK		6.00000
CXXXXXOO	C-MILK		6.00000			
CXXXXOOO	Z	-	94.70000	CORN	-	128.50000
CXXXXOOO	CROPLAND		1.00000	PUMPOP		1.00000
CXXXXOOO	DRYING		128.00000	INTEREST		124.00000
CXXXXOOO	N-FERT		136.00000	P20		30.00000
CXXXXOOO	C-18		6.00000	C-PRE		6.00000
CXXXXOOO	C-PRE-T		6.00000	C-SILK		6.00000
CXXXOOXX	Z	-	94.70000	CORN	-	129.60000
CXXXOOXX	CROPLAND		1.00000	PUMPOP		1.00000
CXXXOOXX	DRYING		129.00000	INTEREST		124.00000
CXXXOOXX	N-FERT		137.00000	P20		30.00000
CXXXOOXX	C-PRE		6.00000	C-18		6.00000
CXXXOOXX	C-PRE-T		6.00000	C-SD		6.00000
CXXXOOXX	C-HD		6.00000			
CXXOXXXX	Z	-	94.70000	CORN	-	133.70000
CXXOXXXX	CROPLAND		1.00000	PUMPOP		1.00000
CXXOXXXX	DRYING		133.00000	INTEREST		125.00000
CXXOXXXX	N-FERT		143.00000	P20		30.00000
CXXOXXXX	C-PRE		6.00000	C-18		6.00000
CXXOXXXX	C-SILK		6.00000	C-MILK		6.00000
CXXOXXXX	C-SD		6.00000	C-HD		6.00000
CXXOXOXO	Z	-	94.70000	CORN	-	129.10000
CXXOXOXO	CROPLAND		1.00000	PUMPOP		1.00000
CXXOXOXO	DRYING		129.00000	INTEREST		124.00000
CXXOXOXO	N-FERT		137.00000	P20		30.00000
CXXOXOXO	C-PRE		6.00000	C-18		6.00000
CXXOXOXO	C-SILK		6.00000	C-SD		6.00000
CXXOOXXX	Z	-	94.70000	CORN	-	122.90000
CXXOOXXX	CROPLAND		1.00000	PUMPOP		1.00000
CXXOOXXX	DRYING		122.00000	INTEREST		123.00000
CXXOOXXX	N-FERT		129.00000	P20		30.00000
CXXOOXXX	C-PRE		6.00000	C-18		6.00000
CXXOOXXX	C-MILK		6.00000	C-SD		6.00000
CXXOOXXX	C-HD		6.00000			
CXOXXXXX	Z	-	94.70000	CORN	-	127.60000
CXOXXXXX	CROPLAND		1.00000	PUMPOP		1.00000
CXOXXXXX	DRYING		127.00000	INTEREST		124.00000

CXOXXXXX	N-FERT		135.00000	P20		30.00000
CXOXXXXX	C-PRE		6.00000	C-PRE-T		6.00000
CXOXXXXX	C-SILK		6.00000	C-MILK		6.00000
CXOXXXXX	C-SD		6.00000			
CXOXOXOX	Z	-	94.70000	CORN	-	118.90000
CXOXOXOX	CROPLAND		1.00000	PUMPOP		1.00000
CXOXOXOX	DRYING		118.00000	INTEREST		121.00000
CXOXOXOX	N-FERT		123.00000	P20		25.00000
CXOXOXOX	C-PRE		6.00000	C-PRE-T		6.00000
CXOXOXOX	C-MILK		6.00000	C-HD		6.00000
CXOOXXXX	Z	-	94.70000	CORN	-	112.20000
CXOOXXXX	CROPLAND		1.00000	PUMPOP		1.00000
CXOOXXXX	DRYING		112.00000	INTEREST		119.00000
CXOOXXXX	N-FERT		115.00000	P20		25.00000
CXOOXXXX	C-PRE		6.00000	C-SILK		6.00000
CXOOXXXX	C-MILK		6.00000	C-SD		6.00000
CXOOXXXX	C-HD		6.00000			
CXOOOXXX	Z	-	94.70000	CORN	-	103.70000
CXOOOXXX	CROPLAND		1.00000	PUMPOP		1.00000
CXOOOXXX	DRYING		103.00000	INTEREST		117.00000
CXOOOXXX	N-FERT		103.00000	P20		25.00000
CXOOOXXX	C-PRE		6.00000	C-MILK		6.00000
CXOOOXXX	C-SD		6.00000	C-HD		6.00000
CXOOOOXX	Z	-	94.70000	CORN	-	72.60000
CXOOOOXX	CROPLAND		1.00000	PUMPOP		1.00000
CXOOOOXX	DRYING		72.00000	INTEREST		112.00000
CXOOOOXX	N-FERT		69.00000	P20		25.00000
CXOOOOXX	C-PRE		6.00000	C-SD		6.00000
CXOOOOXX	C-HD		6.00000			
MXXXXO	Z	-	69.20000	MILO	-	126.50000
MXXXXO	CROPLAND		1.00000	PUMPOP		1.00000
MXXXXO	DRYING		126.00000	INTEREST		98.00000
MXXXXO	N-FERT		132.00000	P20		30.00000
MXXXXO	GS-PRE		6.00000	GS-12		6.00000
MXXXXO	GS-BOOT		6.00000	GS-HEAD		6.00000
MXXXOO	Z	-	69.20000	MILO	-	128.50000
MXXXOO	CROPLAND		1.00000	PUMPOP		1.00000
MXXXOO	DRYING		128.00000	INTEREST		98.00000
MXXXOO	N-FERT		135.00000	P20		30.00000
MXXXOO	GS-PRE		6.00000	GS-12		6.00000
MXXXOO	GS-BOOT		6.00000			
MXXOOO	Z	-	69.20000	MILO	-	118.00000
MXXOOO	CROPLAND		1.00000	PUMPOP		1.00000
MXXOOO	DRYING		118.00000	INTEREST		96.00000
MXXOOO	N-FERT		121.00000	P20		30.00000
MXXOOO	GS-PRE		6.00000	GS-12		6.00000
MXOXOO	Z	-	69.200000	MILO	-	118.00000
MXOXOO	CROPLAND		1.00000	PUMPOP		1.00000
MXOXOO	DRYING		118.00000	INTEREST		96.00000
MXOXOO	N-FERT		121.00000	P20		30.00000
MXOXOO	GS-PRE		6.00000	GS-BOOT		6.00000
MXOOXO	Z	-	69.20000	MILO	-	113.00000
MXOOXO	CROPLAND		1.00000	PUMPOP		1.00000
MXOOXO	DRYING		113.00000	INTEREST		95.00000

MXOOXO	N-FERT		114.00000	P20		30.00000
MXOOXO	GS-PRE		6.00000	GS-HEAD		6.00000
MXOOOO	Z	-	69.200000	MILO	-	94.50000
MXOOOO	CROPLAND		1.00000	PUMPOP		1.00000
MXOOOO	DRYING		94.00000	INTEREST		89.00000
MXOOOO	N-FERT		89.00000	P20		25.00000
MXOOOO	GS-PRE		6.00000			
MOOXOO	Z	-	69.20000	MILO	-	95.50000
MOOXOO	CROPLAND		1.00000	PUMPOP		1.00000
MOOXOO	DRYING		95.00000	INTEREST		90.00000
MOOXOO	N-FERT		91.00000	P20		25.00000
MOOXOO	GS-BOOT		6.00000			
MFALLOW	Z	-	59.00000	MILO	-	33.00000
MFALLOW	CROPLAND		2.00000	INTEREST		59.00000
BXXXXXX	Z	-	59.00000	BEANS	-	34.20000
BXXXXXX	CROPLAND		1.00000	PUMPOP		1.00000
BXXXXXX	INTEREST		65.00000	P20		20.00000
BXXXXXX	B-PRE		6.00000	B-1		4.00000
BXXXXXX	B-2		4.00000	B-3		4.00000
BXXXXXX	B-4		4.00000	B-5		4.00000
BXXXXXO	Z	-	59.90000	BEANS	-	33.50000
BXXXXXO	CROPLAND		1.00000	PUMPOP		1.00000
BXXXXXO	INTEREST		65.00000	P20		20.00000
BXXXXXO	B-PRE		6.00000	B-1		4.00000
BXXXXXO	B-2		4.00000	B-3		4.00000
BXXXXXO	B-4		4.00000			
BXXOXOX	Z	-	59.900000	BEANS	-	26.60000
BXXOXOX	CROPLAND		1.00000	PUMPOP		1.00000
BXXOXOX	INTEREST		65.00000	P20		20.00000
BXXOXOX	B-PRE		6.00000	B-1		4.00000
BXXOXOX	B-3		4.00000	B-5		4.00000
BXOXXXX	Z	-	59.90000	BEANS	-	31.20000
BXOXXXX	CROPLAND		1.00000	PUMPOP		1.00000
BXOXXXX	INTEREST		65.00000	P20		20.00000
BXOXXXX	B-PRE		6.00000	B-2		4.00000
BXOXXXX	B-3		4.00000	B-4		4.00000
BXOXXXX	B-5		4.00000			
BXOXXXO	Z	-	59.90000	BEANS	-	29.50000
BXOXXXO	CROPLAND		1.00000	PUMPOP		1.00000
BXOXXXO	INTEREST		65.00000	P20		20.00000
BXOXXXO	B-PRE		6.00000	B-2		4.00000
BXOXXXO	B-3		4.00000	B-4		4.00000
BXOXOXO	Z	-	59.90000	BEANS	-	29.50000
BXOXOXO	CROPLAND		1.00000	PUMPOP		1.00000
BXOXOXO	INTEREST		65.00000	P20		20.00000
BXOXOXO	B-PRE		6.00000	B-2		4.00000
BXOXOXO	B-4		4.00000			
BXOOXOO	Z	-	59.90000	BEANS	-	24.30000
BXOOXOO	CROPLAND		1.00000	PUMPOP		1.00000
BXOOXOO	INTEREST		65.00000	P20		20.00000
BXOOXOO	B-PRE		6.00000	B-3		4.00000
WXXOOO	Z	-	36.30000	WHEAT	-	67.00000
WXXOOO	CROPLAND		1.00000	PUMPOP		1.00000
WXXOOO	INTEREST		53.00000	N-FERT		80.00000

WXX000	P20		15.00000	W-PRE		6.00000
WXX000	W-JOINT		6.00000			
WXOXOX	Z	-	36.30000	WHEAT	-	61.00000
WXOXOX	CROPLAND		1.00000	PUMPOP		1.00000
WXOXOX	INTEREST		52.00000	N-FERT		75.00000
WXOXOX	P20		15.00000	W-PRE		6.00000
WXOXOX	W-BOOT		6.00000	W-MILK		6.00000
WXOXOO	Z	-	36.30000	WHEAT	-	65.30000
WXOXOO	CROPLAND		1.00000	PUMPOP		1.00000
WXOXOO	INTEREST		53.00000	N-FERT		80.00000
WXOXOO	P20		15.00000	W-PRE		6.00000
WXOXOO	W-BOOT		6.00000			
WXOOOX	Z	-	36.30000	WHEAT	-	64.40000
WXOOOX	CROPLAND		1.00000	PUMPOP		1.00000
WXOOOX	INTEREST		53.00000	N-FERT		80.00000
WXOOOX	P20		15.00000	W-PRE		6.00000
WXOOOX	W-BOOT		6.00000			
WXOOOO	Z	-	36.30000	WHEAT	-	63.60000
WXOOOO	CROPLAND		1.00000	PUMPOP		1.00000
WXOOOO	INTEREST		53.00000	N-FERT		80.00000
WXOOOO	P20		15.00000	W-PRE		6.00000
WFALLOW	Z	-	21.50000	WHEAT	-	30.00000
WFALLOW	CROPLAND		2.00000	INTEREST		28.00000
WFALLOW	N-FERT		25.00000	P20		10.00000
CORN$	Z		3.00000	CORN		1.00000
BEANS$	Z		7.23000	BEANS		1.00000
MILO$	Z		2.64000	MILO		1.00000
WHEAT$	Z		3.81000	WHEAT		1.00000
DRY$	Z	-	.10000	DRYING	-	1.00000
N$	Z	-	.16000	N-FERT	-	1.00000
P20$	Z	-	.25000	P20	-	1.00000
INT$	Z	-	.07000	INTEREST	-	1.00000
PUMP$	Z	-	7.17460	PUMPOP	-	.85000

RHS

B	CROPLAND	160.00000	NOVMARAP	5472.00000
B	APR26-9	891.00000	MAY10-23	891.00000
B	MAY24-1	573.00000	JUN2-8	445.00000
B	JUN9-12	255.00000	JUN13-20	509.00000
B	JUN21-10	1136.00000	JUL11-20	636.00000
B	JUL21-23	191.00000	JUL24-28	318.00000
B	JUL29-30	127.00000	JUL31-6	445.00000
B	AUG7-10	255.00000	AUG11-20	636.00000
B	AUG21-23	191.00000	AUG24-2	636.00000
B	SEP3-5	191.00000	SEP6-15	636.00000

Appendix B

TABLE B1

BUDGETED ACTIVITY FOR FLOOD IRRIGATED CORN

Variable Cost (per acre)[1]	Full (36") Irrigation	18" Irrigation
Labor ($4.00/hour)[2]	$14.40	$12.96
Seed	18.00	18.00
Herbicide $25, Insecticide $11	36.00	36.00
Nitrogen ($.16/pound)[3]	23.21	14.48
P_2O_5 ($.25/pound)[4]	7.00	6.25
Pumping	63.18	35.80
Crop Machinery Repairs	12.00	12.00
Drying ($.10/bu.)	13.50	9.40
Miscellaneous	3.00	3.00
Interest 1/2 Variable Costs @ 14%	14.48	11.27
TOTAL VARIABLE COST	$221.37	$175.36

1 Modified version of: Don D. Pretzer. "Flood Irrigated Corn" KSU Farm Management Guide MF-578, Cooperative Extension Service, Kansas State University (Nov. 1980).

2 Labor time will vary with number of times of irrigation from 3.75 hours to 3.07 hours.

3 Nitrogen rate was calculated using: Nitrogen = −34.5 + 1.33 X bu/A.

4 P_2O_5 rate was calculated using: 25 pounds for 90 to 120 bu/A yields and 30 pounds for 120 to 150 bu/A yields.

5 Pumping cost were calculated using: −19.715523 − 0.003204 X GPM + 0.085 X Lift + 1.065039 X Inches + 6.79289 X Energy Cost assuming 185 foot lift and $2.00 Energy Cost.

TABLE B2

BUDGETED ACTIVITY FOR FLOOD IRRIGATED GRAIN SORGHUM

Variable Cost (per acre)[1]	Full (30") Irrigation	6" Irrigation	Fallow
Labor ($4.00/hour)[2]	$12.88	$10.04	$ 6.56
Seed	3.00	3.00	1.50
Herbicide $25, Insecticide $10	25.00	25.00	25.00
Nitrogen[3]	21.28	14.56	
P_2O_5[3]	7.00	6.25	
Fuel-Oil Crop	15.00	15.00	15.00
Pumping[4]	54.05	17.54	
Crop Machinery Repairs	14.00	12.00	8.00
Drying ($.10/bu)	13.10	9.60	
Miscellaneous	3.00	3.00	3.00
Interest 1/2 Variable Cost @ 14%	11.78	8.20	4.13
TOTAL VARIABLE COST	$180.09	$124.10	$63.19

1 Modified version of: Don D. Pretzer. "Flood Irrigated Grain Sorghum" KSU Farm Management Guide MF-579, Cooperative Extension Service, KSU (Nov. 1980).

2 Labor time will vary with number of times of irrigation from 3.22 hours to 1.64 hours. Orlan H. Buller, Larry N. Langemeier, and John L. Kasper "Labor Requirements of Western Kansas Irrigated and Dry-land Crops" KSU Experiment Station Bulletin 593 (Oct. 1975).

3 Recommendations of David Whitney, Professor of Agronomy, KSU.

4 Pumping cost were calculated using: -19.715523 - 0.003204 X GPM + 0.085 X Lift + 1.065039 X Inches + 6.79289 X Energy Cost: assuming 185 foot lift and $2.00 Energy cost. J.R. Williams, J.R. Sleper, O.W. Buller. "The Impact of Selected Variables on Operating Costs of Irrigation Systems in Western Kansas", Department of Agricultural Economics, KSU.

TABLE B3

BUDGETED ACTIVITY FOR FLOOD IRRIGATED SOYBEANS

Variable Cost (per acre)[1]	Full (26") Irrigation	10" Irrigation
Labor ($4.00/hour)[2]	$ 12.96	$ 10.48
Seed	12.00	12.00
Herbicide	10.00	10.00
P_2O_5[3]	5.00	5.00
Fuel-Oil Crop	14.00	14.00
Pumping[4]	47.97	23.63
Crop Machinery Repairs	12.00	12.00
Miscellaneous	3.00	3.00
Interest 1/2 Variable Cost @ 14%	8.19	6.31
TOTAL VARIABLE COST	$125.12	$ 96.42

1 Modified version of: Don D. Pretzer. "Flood Irrigated Soybeans" KSU Farm Management Guide MF-577, Cooperative Extension Service, Kansas State Univesity (Nov. 1980).

2 Labor time will vary with number of times of irrigation from 3.3 hours to 2.62 hours. Orlan H. Buller, Larry N. Langemeier, and John L. Kasper "Labor Requirements of Western Kansas Irrigated and Dryland Crops" Agricultural Experiment Station Bulletin 593 (Oct. 1975).

3 Recommendation of David Whitney, Professor of Agronomy, KSU.

4 Pumping cost were calculated using: -19.715523 - 0.003204 X GPM + 0.085 X Lift + 1.065039 X Energy Cost assuming 185 foot lift and $2.00 Energy Cost. J.R. Williams, J.R. Sleper, O.W. Buller. "The Impact of Selected Variables on Operating Costs of Irrigation Systems in Western Kansas" Department of Agricultural Economics, KSU.

TABLE B4

BUDGETED ACTIVITY FOR FLOOD IRRIGATED WHEAT

Variable Cost (per acre)[1]	Full (24") Irrigation	12" Irrigation	Fallow Irrigation
Labor ($4.00/hour)[2]	$ 9.68	$ 8.56	$ 7.68
Seed	6.00	6.00	3.00
Nitrogen[3]	6.40	5.76	4.00
P_2O_5[3]	3.75	3.75	2.50
Fuel-Oil Crop	10.00	10.00	6.00
Pumping[4]	44.93	26.67	
Crop Machinery Repairs	9.60	9.60	5.00
Miscellaneous	3.00	3.00	3.00
Interest 1/2 Variable Cost @ 14%	6.54	5.13	2.18
TOTAL VARIABLE COST	$99.90	$78.47	$33.37

[1] Modified version of: Don D. Pretzer. "Flood Irrigated Wheat", KSU Farm Management Guide MF-590. Cooperative Extension Service, Kansas State University (Nov. 1980).

[2] Labor time will vary with number of times of irrigation from 2.42 hours to 1.92 hours. Orlan H. Buller, Larry N. Langemeier, and John L. Kasper "Labor Requirements of Western Kansas Irrigated and Dryland Crops" KSU Experiment Station Bulletin 593 (Oct. 1975).

[3] Recommendations of David Whitney, Professor of Agronomy, KSU.

[4] Pumping cost were calculated using: -19.715523 - 0.003204 X GPM + 0.085 X Lift + 1.065039 X Inches + 6.79289 X Energy Cost; assuming 185 foot lift and $2.00 Energy Cost. J.R. Williams, J.R. Sleper, O.W. Buller. "The Impact of Selected Variables on Operating Costs of Irrigation Systems in Western Kansas", Department of Agricultural Economics, KSU.

LIMITED IRRIGATION CROP SELECTION:
A LINEAR PROGRAMMING MODEL

by

LARRY F. ROEDER

B.S., KANSAS STATE UNIVERSITY, 1980

AN ABSTRACT OF A MASTER'S THESIS

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MASTER'S OF SCIENCE

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Manhattan, Kansas

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ABSTRACT

Roeder, Larry, M.S. Kansas State University, August, 1981. Limited Irrigation Crop Selection: A Linear Programming Model. Major Professor: Orlan H. Buller.

As the supply of water available for irrigation becomes more limiting in southwestern Kansas, the decrease in revenues caused by the limited quantity of water available for crops can be offset by raising a combination of crops that are the most responsive to the water when it is available; consequently maintaining profits at levels near those when water is not so limiting. As the supply of irrigation water decreases to where there is not enough water available for full irrigation of corn, rather than limit the total irrigated acres. The available water is to be applied to the total developed area but limited to combinations of critical periods of crops most responsive to the water when it is available.

A linear program model was constructed for a 160 acre flood irrigated field in southwestern Kansas with the irrigation pumps powered by natural gas lifting water 200 feet. Six different rates of irrigation water applications from 200 GPM to 1200 GPM were used as limitations for six runs of the linear programming model.

Data from the Garden City Experiment Station was used on crop response to water limitations at various stages and combinations of stages. Four crops are used in the study; corn, soybeans, grain sorghum, and wheat. The model selects from 13 water management practices available for corn, seven water management practices available for soybeans, eight

water management practices available for grain sorghum, and six water management practices available for wheat.

The experiments at Garden City have been conducted since 1974; however, data was selected for use in the model for years 1975 and 76, years considered to have normal rainfall. Cost data on the crops were derived from a combination of the Kansas Cooperative Extension Service, recommendations of the Agronomy Department at Kansas State University, and a pumping program from the Economics Department at Kansas State University.

Results of the model indicate in order to maximize profits the farmer should plant as much corn as possible that can be grown without allowing the crop to experience ET deficit. This is possible for well outputs of 400 GPM and greater of the 13 possible water management practices for corn. In the model only, two fully irrigated activities are selected.

With limited water, the model selects only partial irrigated grain sorghum and wheat. As water becomes less limiting, more corn acreage is selected replacing grain sorghum and wheat. With 1200 GPM, the 160 acres is planted to 117 acres of fully irrigated corn.