AN ECONOMIC ANALYSIS OF THE INTERTEMPORAL ALLOCATION OF GROUND WATER IN THE CENTRAL OGALLALA FORMATION

By

SOLOMON BEKURE

Bachelor of Science
Haile Selassie I University
Alemaya, Ethiopia
1963

Master of Science
Oklahoma State University
Stillwater, Oklahoma
1967

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of the Oklahoma State University
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Thesis Approved:

Vernon R. Eidman
Thesis Adviser

Luther G. Tweeten

Robert D Morrison

R D Davis

D Durham
Dean of the Graduate College

PREFACE

This dissertation is concerned with the investigation of the intertemporal allocation of ground water in the Central Ogallala Formation. The analysis is divided into two parts. In the first part, two recursive linear programming models are developed and used to project the growth and pattern of irrigated crop production, the accompanying gross and net returns in the study area and the resulting rate of ground water depletion from the aquifer in the period 1965-2070. In the second part, two multi-stage sequential decision models are developed and used to test whether the rates of ground water depletion in the first part of the study are optimal.

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I extend my profound gratitude and appreciation to my parents for their guidance and support throughout my educational career. Finally, I dedicate this dissertation to my wife, Zebade and son, Menelik, for assuming the many hardships and sacrifices during the course of this study with patience, faith and understanding.

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CHAPTER I

INTRODUCTION

Farmers in the Great Plains have been relying on irrigation (1) to expand the size of their business, (2) to increase their revenue, and (3) to stabilize their income. The number of irrigated acres doubled in the period 1949-1964.[1] The severe droughts of the 1950's coupled with post war technological advances in commercial fertilizers and irrigation equipment have provided much of the impetus to irrigation development. This rapid expansion of irrigation in the semiarid climate of the Great Plains has (1) effectively reduced the risks and uncertainties characterizing agricultural production under highly variable weather conditions and (2) increased average per acre crop yields, thus contributing to a more stable and increased farm income in the region. This development has called for increased capital expenditures per acre of land irrigated via expanded use of inputs like fertilizers, insecticides, herbicides, machinery and hired labor. As these inputs are purchased off the farm a whole set of economic activities based on the effective demand generated by irrigated agriculture has emerged. Local suppliers of fertilizers, seeds, insecticides, machinery, irrigation equipment, fuel, marketing and financing facilities are active to meet this demand. The net effect of these economic activities has been the production of a larger bundle of commodities and services in the region. Whether this bundle will continue to grow, remain static, or decline in future years depends on the long run prospects for the availability of irrigation water at costs irrigators can afford to pay.

In the production period 1960-1965, about two-thirds of the water used for irrigation in the Great Plains was pumped from underground aquifers. The remaining one-third came from surface sources.[2] In some sectors of the Great Plains, such as the area investigated in this study, ground water provides practically all of the water used for irrigation, municipal and industrial purposes. In such areas the extensive irrigation development of the last two decades has resulted in an annual withdrawal of ground water in excess of natural recharge. As land suitable for irrigation development is in plentiful supply the acreage irrigated is expected to increase.[3] This process renders the supply of ground water a stock resource subject to the eminence of eventual economic and/or physical exhaustion. Physical exhaustion occurs when the aquifer ceases to yield water to wells. Economic exhaustion sets in when declining water tables increase the cost of pumping water from the aquifer to the point where the total cost exceeds the total return from its use. In other words, economic exhaustion occurs when the per unit value in use of ground water becomes negative. The fact that there is such a possibility raises questions on the long run supply of water for irrigation. It is the general purpose of this study to investigate the availability of ground water in future years for part of the Great Plains area underlain by the aquifer called the Central Ogallala Formation.

Description of the Study Area

Location and Size

The Ogallala Formation is an unconsolidated aquifer named after the town of Ogallala, Nebraska.[4] This formation underlies most of the Great Plains area extending from the southern half of South Dakota to a few miles north of the Pecos River in southern Texas. The formation runs through parts of eastern Colorado, Nebraska, western Kansas, eastern New Mexico, the Oklahoma Panhandle and the northern and southern high plains of Texas.[5] The sediments that compose the formation are believed to have been eroded from the Rocky Mountains and carried by streams to be deposited in the eroded and dissected surfaces of the pre-Ogallala rocks ranging in age from Permian to Cretaceous.[6] The easterly gradient of the base of the formation is attributed to this phenomenon. After the cuts and dips in these rocks were filled, water continued to shift and deposit the sediment over the entire area described above. Conditions changed over time and streams started to cut into the unconsolidated deposits.[7] The North Platt River, the Arkansas River and the Canadian River have cut completely through the formation into the older rocks. Consequently, unconnected distinct subdivisions of the Ogallala Formation can be identified. This study is concerned with the central part of the Ogallala Formation bounded by the Arkansas River on the north and the South Canadian River on the south. It includes a small portion of two counties in southeastern Colorado, eight counties in southwestern Kansas, the three Panhandle counties of Oklahoma and seven counties in the northern part of the Texas High Plains. The land area overlying this hydrologic subdivision is estimated to be about

17,500 square miles. Figure 1 outlines the study area and shows the counties included.

Climate

The study area is typical of the High Plains semiarid region. It is characterized by low precipitation, low relative humidity, wide daily and seasonal variation in temperature and moderately high wind velocity. The mean annual precipitation is about 19 inches. However, its occurrence is highly variable, ranging from a low of about eight inches to a high of about 31 inches. Most of the precipitation is received in the form of summer showers. Table XXXII, Appendix B, shows the distribution of mean monthly rainfall of the study area compiled from a 25 year period (1941-1965) for the counties involved. Summer temperatures of over 100 degrees and winter temperatures of less than zero occur on occasions. The hot summer winds contribute to a high rate of evapotranspiration which is reported to remove as high as 98 percent of the precipitation that falls on the land area.[8] The growing season averages less than 190 days between the last killing frost (usually occurring sometime in the last two weeks of April) and the first killing frost (usually occurring sometime in the last three weeks of October).

Soil and Water Resources

The major soil type of the study area is clay loam interspersed with silty loam and silty clay loam soils. Together they make up about 67 percent of the total irrigable soils in the study area. The remaining 23 percent of the irrigable soils are sandy loam soils. As the

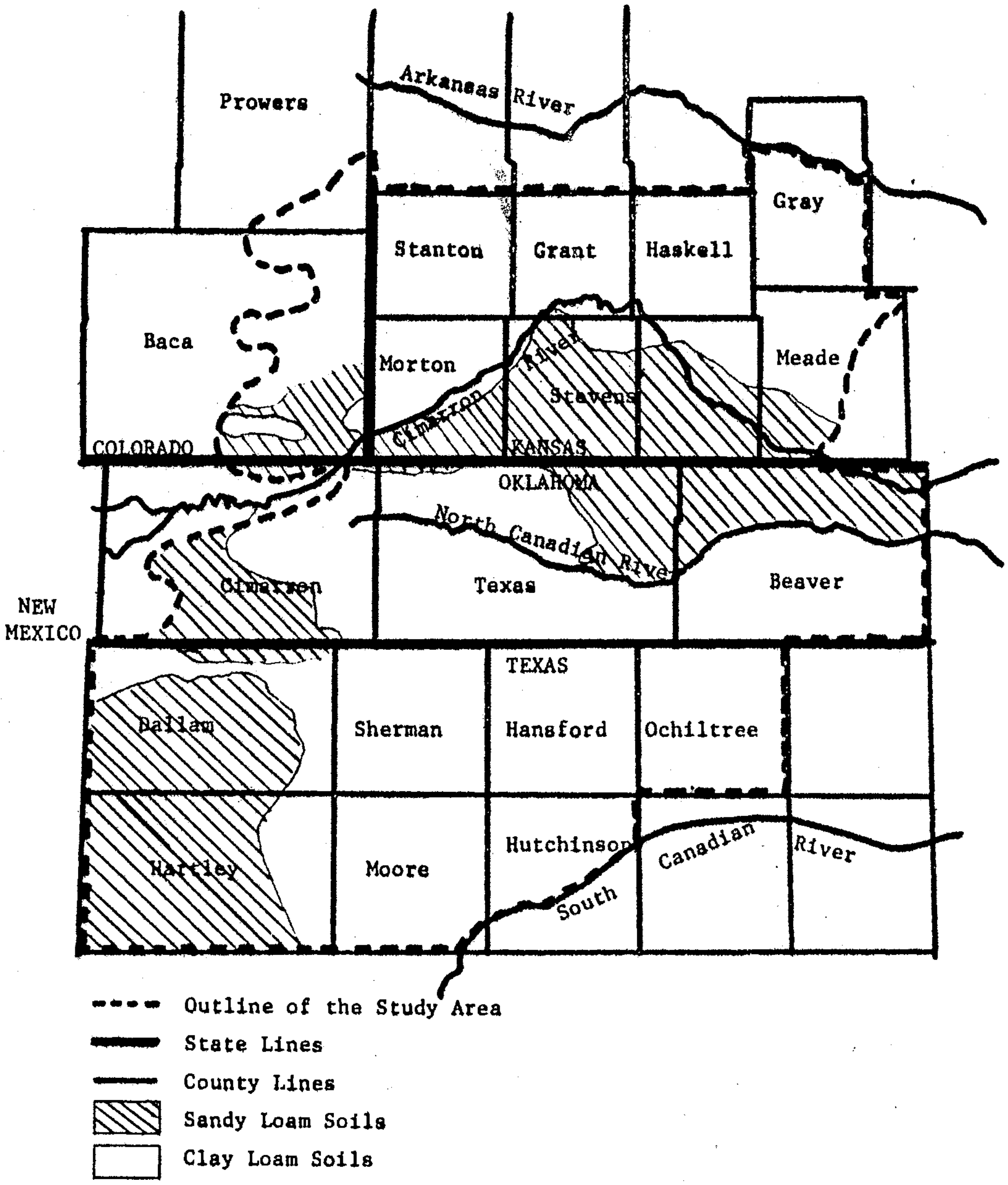

Figure 1. The Study Area

shaded area in Figure 1 shows, the sandy soils are concentrated in two sections of the study area. One section includes a narrow strip in the southeastern portion of Baca County (Colorado), the southern one-third of Morton County (Kansas), and then fans out to include most of Stevens and Seward and the southwestern tip of Meade Counties (Kansas), as well as the northern one-third of Beaver and the northeastern tip of Texas Counties in Oklahoma. The second sandy section occupies the western part of Cimarron County in Oklahoma and almost all of the area in Dallam and Hartley Counties in Texas. The rest of the study area is composed of clay loam soils. Most of the clay loam soils are deep, nearly level and well drained, suitable for furrow or flood irrigation and respond well to applications of fertilizer. Most of the sandy soils have steep slopes and appear to be suitable only for sprinkler irrigation.

The geologic setting and the hydrologic characteristics of the Central Ogallala Formation as the water resource of the study area are presented in Appendix D.

Type of Agriculture

Agriculture is the major industry upon which much of the economic development of the study area has been dependent. The production of wheat, grain sorghum and beef cattle dominates the type of agriculture practiced. Due to the relative shortness of the growing season, high-valued cash crops like cotton and peanuts cannot be grown successfully in much of the area. Wheat and grain sorghum are the principal cash crops. In the census year 1964, these two crops accounted for 92.09 percent of the total irrigated acreage of the eight main irrigated crops in the area, and 98.65 percent of the total dryland acreage of these eight crops. Table XXXIII of Appendix C presents the production pattern of the eight principal irrigated crops as reported in the 1964 census of agriculture.

In recent years cattle feeding in the study area has been characterized by rapidly increasing numbers of large-scale commercial feedlots. The number of cattle fed in such enterprises in the Oklahoma Panhandle increased from 131,212 in the 1966-1967 production period to 407,362 in the 1969-1970 production period, which is a very rapid growth.[9] Similar growth in the number of cattle fed has been observed in the rest of the study area.[10] This rapid development in the cattle feeding industry of the study area has tremendously increased the demand for feed grains, hay and silage. As this development is expected to continue for the foreseeable future, the irrigated production of these crops is expected to increase very rapidly.

Development of Irrigation

Wells to tap the Central Ogallala Formation were drilled as early as 1932 in Oklahoma.[11] In Colorado and Kansas the early wells were drilled around 1940.[12] However, the greatest development was after 1950. The advent of large economical and efficient pumping systems, notably the vertical turbine pump, coupled with the severe drought of 1952 through 1956 accelerated the growth of irrigation. The portion of the study area in Texas experienced the most rapid growth in irrigation both in absolute and relative terms followed by Oklahoma, Kansas and Colorado in that order. The breakdown of irrigation development for the period 1950-1965 by state is given in Table I. Figure 2 shows

TABLE I

ESTIMATED NUMBER OF IRRIGATED ACRES AND ACRE FEET OF GROUND WATER APPLIED IN THE STUDY AREA 1950-1965[1]

	Colorado		Kansas		Oklahoma		Texas		Total		Year to Year Change in Total		
Year	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Net Withdrawal[2]
1950	8,584	14,593	34,012	57,820	10,024	17,041	16,944	28,805	69,564	118,259	11,203	23,084	-151,819
1951	9,027	15,797	42,085	73,649	10,458	18,302	19,197	33,595	80,767	141,343	16,193	46,758	-128.735
1952	9,470	18,372	53,376	103,549	10,892	21,130	23,222	45,050	96,960	188,101	32,214	70,247	- 81,977
1953	9,913	19,826	67,120	134,240	16,985	33,970	35,156	70,312	129,174	258,348	64,626	125,376	- 11,730
1954	10,356	20,505	86,904	172,070	23,078	45,694	73,462	145,455	193,800	383,724	110,109	254,486	113,646
1955	12,097	25,404	135,745	285,065	35,478	74,504	120,589	253,237	303,909	638,210	196,716	618,358	368,132
1956	13,838	34,733	150,942	378,864	64,456	161,785	271,389	681,186	500,625	1,256,568	119,379	14,440	986,490
1957	15,580	31,939	235,693	483,171	69,124	141,704	299,607	614,194	620,004	1,271,008	13,941	-167,943	1,000,093
1958	16,213	28,211	249,573	434,257	61,567	107,127	306,592	533,470	633,945	1,103,065	28,337	29,437	832,987
1959	16,846	28,807	256,409	438,459	63,280	108,209	325,747	557,027	662,282	1,132,502	39,439	60,424	862,424
1960	18,940	32,198	270,670	460,139	63,390	107,763	348,721	592,826	701,721	1,192,926	29,356	93,770	922,848
1961	21,034	37,020	279,516	491,948	63,500	111,760	367,027	645,968	731,077	1,286,696	64,462	153,230	1,016,618
1962	23,128	41,862	299,865	542,756	63,609	115,132	408,937	740,176	795,539	1,439,926	188,937	588,937	1,169,848
1963	25,222	51,957	322,176	663,683	73,962	152,362	563,116	1,160,018	984,476	2,028,020	297,428	958,817	1,749,942
1964	27,314	63,642	347,999	810,838	95,443	222,382	811,148	1,889,975	1,281,904	2,986,837	246,885	-663,078	2,708,759
1965	29,406	44,697	379,248	576,457	116,925	177,726	1,003,210	1,524,879	1,528,789	2,323,759			

[1] Estimated rate of water application taken from "Ground Water in the Cimarron River Basin", 1966, prepared by the U. S. Geologic Survey Water Resource Division for the U. S. Corps of Engineers, Tulsa District, p. 33.

[2] Acre feet applied minus recharge. Negative figures indicate a net addition to storage.

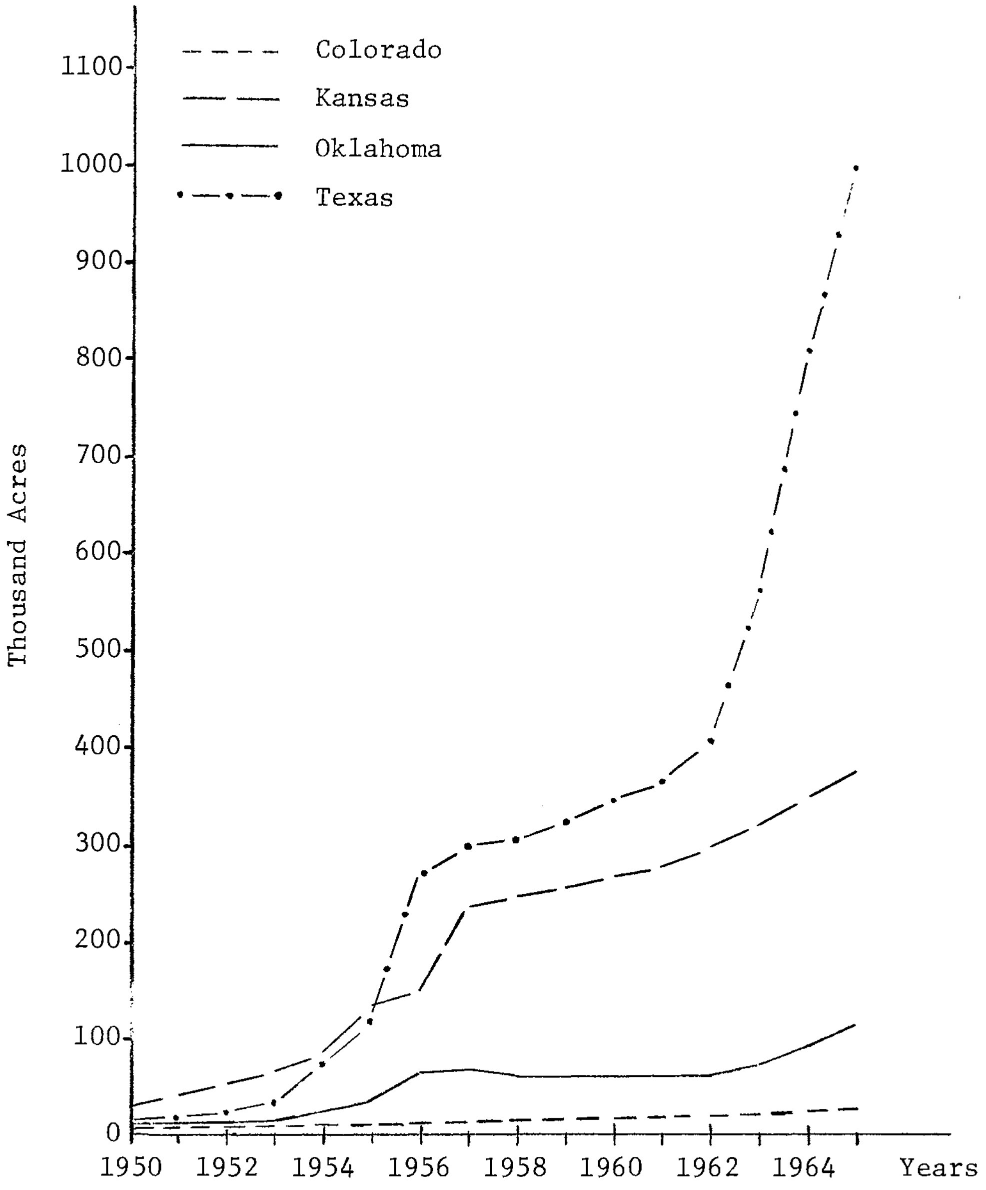

Figure 2. Growth of Irrigation in the Study Area by States 1950-1965

the growth of irrigated acres for each state. During the 1950-1965 period, the number of irrigated acres increased from 17,000 to 1,003,000 in Texas, from 1,000 to 117,000 in Oklahoma, from 34,000 to 379,000 in Kansas and from 9,000 to 29,000 in Colorado. By 1965, 13.71 percent of the total study area or 19.01 percent of the acres suitable for irrigation was irrigated (see Table II).

The net volume of water withdrawn from the Central Ogallala Formation has continued to increase with the expansion of irrigation. While recharge is estimated to be about 0.27 million acre feet,[13] the annual withdrawal of water from the aquifer in recent years has exceeded 2.0 million acre feet. As shown in the last column of Table I, the first overdraft of the aquifer occurred around 1954 when a net of 113,650 acre feet of water was pumped. By 1965 the overdraft had increased to over 2.7 million acre feet per year. The amount of water withdrawn for irrigation is expected to increase annually during the next several years. This implies the rate of annual overdraft will be even greater in the future.

The consequence of continued overdraft of the aquifer is a reduction in the thickness of the water-saturated material and an increase in the pump lift, thereby increasing the per unit cost of recovering water from the aquifer. Fader and his collegues report that in the heavily pumped areas of Grant and Stanton Counties (Kansas) the water table declined as much as 70 feet during a period of 18 years (1942-1960). Based on observations during the same period they calculated a weighted average annual decline of 2.01 feet.[14] In Texas, Buchanan reports an average annual decline of 1.6 feet for the ten year period 1956-1965. However, in most of the counties average annual decline has

TABLE II

RELATIVE STATUS OF IRRIGATION DEVELOPMENT 1965

State	Irrigable acres	Non irrigable acres	Total acres	Acres irrigated 1965	Acres irrigated in 1965 as a percent of	
					Irrigable acres	Total acres
Colorado	526,568	90,153	616,721	29,406	5.58	4.76
Kansas	2,606,335	449,699	3,056,034	379,248	14.55	12.41
Oklahoma	2,162,655	891,192	3,053,847	116,925	5.41	3.83
Texas	2,745,357	1,677,379	4,422,736	1,003,210	36.54	22.68
Study area	8,040,915	3,108,423	11,149,338	1,524,879	19.01	13.71

exceeded two feet since 1963.[15] The development of irrigation in the Oklahoma and Colorado portion of the study area has not been as extensive as in the Texas and Kansas portion. Consequently, the decline in the water table for these area has been lower. In fact in some years following unusually large storms appreciable rises have been registered in Baca, Cimarron and Beaver Counties.[16] However, as irrigation continues and heavy overdraft develops, ground water is expected to move to areas of low pressure and significant declines will be observed.

The Problem and Objectives of the Study

Developments of the past decade clearly indicate that the water table of the Central Ogallala Formation will decline and the ground water in storage will inevitably diminish in the future. As the water table declines the unit cost of pumping water will increase. *Ceteris paribus*, this will progressively decrease net returns from each unit of irrigated crop production as time proceeds. Sooner or later, it will be uneconomical to pump water for irrigation purposes in some parts of the study area. This implies resources once committed to irrigated production will have to revert to dryland farming. The adjustment from irrigation to dryland farming will result in serious primary and secondary reductions of income in the study area. The primary reduction of income entails the higher net returns per acre of production forgone and some of the resources abandoned in switching to dryland farming. The secondary reduction of income involves the losses attributed to reduced land prices, and the economic slump created through the multiplier effect by the reduction of demand for inputs and services that complement irrigated crop production in the study area. How severe the adjustments to the declining water table will be is, in part, determined by how fast the ground water is depleted and, in part, by the actions taken to lessen its adverse effects. Consequently, the questions of concern to all members of the community (land owners, farm operators, businessmen and policy makers alike) are (1) what is the economic life of the water supply in different locations of the study area? (2) at what rates will these lives be approached? (3) what will the economic adjustments in irrigated crop production entail? and (4) what can be done to mitigate the adverse economic effects of the declining water supply over time? If these questions are answered and estimates of the magnitudes of expected changes are available, community leaders can address themselves to the measures necessary to ease the adverse economic effects of the ground water depletion.

This study is the first part of a three-phase investigation of the study area in an effort to provide reasonable estimates of the answers to the questions posed above. The general objective of this study is to present estimates of (1) the growth of irrigation in the study area, (2) the rate of depletion of the aquifer over time and its effects on (a) the pattern of irrigated crop production and (b) the gross and net receipts to irrigated crop production over time. The study also investigates whether the projected rates of ground water depletion are optimal from the standpoint of maximizing the study area's net returns from irrigated crop production in the long run. The specific objectives are (1) to develop a model that (a) depicts the study area's irrigated crop production, (b) projects the growth in irrigation, (c) estimates the resulting rate of ground water withdrawal over time and (d) estimates the changes in gross and net returns to irrigated crop production over time, and (2) to develop a multi-stage sequential decision model that determines the optimum rate of ground water withdrawal for a given planning horizon.

The remainder of this dissertation is organized as follows. Chapter II presents the analytic models used in the analysis of this study. The first portion discusses and describes the two recursive linear programming models used to project the growth of irrigated crop production over time, the accompanying rates of ground water depletion and changes in gross and net returns. The second part of Chapter II discusses the theory of multi-stage sequential decision models and describes how the optimum rate of ground water withdrawal in a given planning horizon can be formulated as a multi-stage sequential decision process amenable to optimization by the dynamic programming technique.

Chapter III describes the methodology and assumptions employed from establishing the benchmark conditions of the soil and water resources of the study area in 1965 to specifying the structural parameters of the two recursive linear programming production models.

Chapters IV and V present the empirical results. In Chapter IV the results of the two production models are presented and analyzed. The data for the multi-stage sequential decision model is developed in the initial portion of Chapter V. The resulting optimal rates of ground water withdrawal, their expected discounted net benefits as computed by the dynamic programming technique under different sets of assumptions, and the policy implications of these results in view of the solutions of the production models are analyzed and discussed in the remainder of the chapter.

Chapter VI contains the summary and conclusions of the study. The limitations of the study and recommendations for further research are also given.

FOOTNOTES

[1] M. L. Cotner, John F. Fritschen, William H. Henebery and Joseph Biniek, *Soil and Water Use Trends in the Great Plains -- Their Implications*, Great Plains Agricultural Council, Publication No. 34 (March, 1969), p. 197.

[2] Ibid.

[3] Glen J. Vollmar, *Irrigated Agriculture -- Potential for the Great Plains*, Great Plains Agricultural Council, Publication No. 34 (March, 1969), p. 41.

[4] J. W. Buchanan, *Geology and Ground Water Resources of the North Plains Ground-Water Conservation District No. 2*, Progress Report No. 2 (1967), p. 7.

[5] George W. Stoe and O. A. Ljungstedt, *Geologic Map of the United States*, U. S. Geologic Survey 1932, Reprinted 1960.

[6] For the meaning of words in italics see Appendix A.

[7] Buchanan, pp. 7-8.

[8] Kansas Water Resources Board, *A Hydrologic Ground-Water Study*, Report No. 16(c) (September, 1967), pp. 2-3, and Texas Agricultural Experiment Station, "Panhandle Economic Program", Texas A & M University, pp. 161-165.

[9] Raymond A. Dietrich, *The Texas-Oklahoma Cattle Feeding Industry: Structure and Operational Characteristics*, Texas Agricultural Experiment Station, Texas A & M University, B-1079 (December, 1968), and Texas County, Oklahoma, Extension Center, "Cattle Feedlots", (Unpub. Mimeo.), Guymon (January, 1970). The figures include cattle fed in Harper County, Oklahoma, which is outside the study area.

[10] The figure available for Texas includes sixteen more counties outside the study area. Since the data is not reported by county any disaggregation will be arbitrary and inaccurate. In general, the 1969-1970 number of cattle fed is more than 300 percent of the figure in the 1966-1967 period.

[11] Stuart L. Schoff, *Geology and Ground Water Resources of Texas County, Oklahoma*, Oklahoma Geological Survey, Bulletin No. 59, Norman (1939), p. 109.

[12] R. W. Beck and Associates, "Ground Water Resources Study Relating to Portions of Prowers, Baca and Las Animas Counties, Colorado" (February, 1967), p. 8, and, Kansas Water Resources Board, p. 4.

[13] For estimation of annual recharge see Appendix D.

[14] Stuart W. Fader, et.al., Geohydrology of Grant and Stanton Counties, Kansas, State Geological Survey of Kansas, Bulletin 168, University of Kansas, Lawrence, Kansas (1964), pp. 14-32.

[15] Buchanan, pp. 41-49.

[16] U. S. Geologic Survey, Water Resource Division, Ground Water in the Cimarron River Basin, prepared for the U. S. Corps of Engineers, Tulsa District (1966), p. 35.

CHAPTER II

THE ANALYTIC MODELS

The Commonality Problem

An underground water supply can be classified as a stock resource, which possesses the property of commonality since proporietors of the overlying land obtain their water from a common reservoir. These proprietors, acting individually in their self interest, may tend to misallocate the intertemporal use of the underground water resource. The optimum allocation of this stock resource among different production periods requires that the rate at which it is used should be such that the present value of the stream of future incomes is a maximum. An irrigating firm using a communal underground water resource does not have complete control over the quantity available to it in future years. The firm saving part of the stock for future production periods cannot depend on having the stock saved available for its use at the cost it expects. The cost of its future water supply is, rather, determined collectively by the action of all irrigators tapping the underground water reservoir. If each firm is not assured of the right to use that part of the stock it saved for its future use at the cost it expects, it acts as if it considers the value of the water in the underground reservoir to be zero as long as it does not pump it. Consequently, the firm's decision will be to maximize net returns to the quantity of water it removes from year to year without reference to its complete planning horizon. The quantity of water pumped by the individual irrigating firm has a negligible effect on future pumping costs and future supplies from its viewpoint; but for all irrigating firms as a group, the current use rate has an adverse effect on the future cost of pumping and the availability of future supplies of water. If irrigating firms have the option of making a group decision, they may wish to ascertain a more dependable future supply at lower costs by reducing the current rate of use.

The first portion of this chapter discusses the production model used to project the rate of ground water withdrawal over time under the assumption that irrigating firms maximize net returns to the stock resource of ground water from one production period to the next. The second part discusses the formulation of the problem of the optimal rate of ground water withdrawal over time as a multi-stage sequential decision model under the assumption that irrigating firms can make a decision on the rate of exploitation of their common stock resource as a group.

The Production Model

The analytic model used to project (1) the growth of irrigation in the study area, (2) the rate of underground water withdrawal, and (3) the pattern of irrigated crop production over time is a recursive linear programming (RLP) model. Basically, the RLP model is an adaptation of the static linear programming (LP) model to changing conditions of time that necessitate the revision of parts of the LP model for period t + 1 based upon the solution of period t and conditions that prevail in period t + 1. The revision may involve the objective function, the input-output coefficients, the right-hand side restrictions, or any combination of them. James M. Henderson was the first to use and test the idea that a profit maximizing LP model with "flexibility" restraints on year to year adjustments can be used as a predictive device. He tested the model to explain changes in the acreages of selected field crops in the United States between 1954 and 1955.[1] Richard H. Day used the model in studying changes in the production of cotton and other alternative crops in the Mississippi Delta during the period 1940-57.[2] Day has been instrumental in popularising the RLP model, and in its adoption by the Farm Production Economic Division, ERS of the USDA in building the national model of agricultural production response.[3]

The RLP model is well suited for the purposes of the first part of this study in that, first, as the overdraft of the aquifer continues in the future, the decline in the water table causes changes in water costs and water availability from one production period to the next; and secondly, the area's supply of crops and irrigated acreage changes from period to period according to an _a priori_ projection, which will be discussed later, all of which necessitate revisions in the production model. Moreover, the solutions of the RLP model (1) constitute an optimum with respect to maximizing net returns, (2) yield the levels of the various crops grown, their irrigated and dryland acreages and (3) give the level of inputs used in the production process. Obtaining all of the results in one package is desirable in achieving the general objectives of the first part of the study.

One major difficulty in the predictive application of the RLP model to regional supply response studies is the task of aggregating. There are far too many farms in the study area to treat each of them as an individual decision making unit in the empirical analysis. Therefore, some level of aggregation is necessary if empirical analysis of the problem is to be of a manageable size. In the past, agricultural economists have been using two approaches. The first approach uses a micro technique of programming representative farms to get optimum solutions and then multiplying them by the number of farms each representative farm represents and sum these products to arrive at the aggregate solution. However, the summing procedure introduces what has been called "aggregation bias" common to such micro techniques. The aggregation bias and the problems of using the micro programming approach have been the subject of wide discussion.[4] Sharples has summarized these discussions and pointed out the need for a new approach in regional supply response studies.[5] The second approach used is a macro technique in which the region is defined as the unit of inquiry rather than the farm, thus yielding aggregate results directly. Implicitly, the macro programming approach considers the whole region or study area as the decision making unit. While eliminating one type of aggregation bias it creates another type in that problems of resource allocation within the farm are completely bypassed. Fixed resources such as tractors, irrigation wells and equipment belong to individual farms and additional investment in such factors of production may depend on equity positions which the macro approach ignores. In addition, implications to the farm firm cannot be made as easily and directly as in the micro programming approach of the representative farm. The advantage of using the macro programming approach lies largely in the fact that data requirements and the time and cost of analysis are substantially less than the micro programming approach. Furthermore, using budgets whose costs and returns are specified on a per acre basis in an LP model may yield approximately the same aggregate values via both models. Sharples points out that past studies indicate the use of the traditional methods of defining representative farms may result in a set of representative farms all of which have the same optimum organization.[6] Richard H. Day has shown that if certain proportionality conditions hold among individual representative farms, i.e., identical input-output coefficients, proportional objective functions and right-hand side restrictions, then macro programming will result in exactly the same values as summing the weighted solutions of the individual representative farms.[7]

In the light of the advantages and disadvantages of both the micro and macro programming approach, it should be emphasized that the answers sought from the empirical analysis should dictate the approach chosen. Since the main purpose of this study is to investigate the availability of ground water in future years and its implications for the entire study area, the macro programming approach is used. The entire area is regarded as a single producing unit stratified by the various combinations of soil and water resource situations. Each soil and water resource stratum is associated with a set of cost and return parameters in the production of the various irrigated crops. The problem to be solved is the combination and levels of crop enterprises to be produced among the various soil and water resource situation strata at different points in time that will maximize total net returns to the study area.

The RLP production model shown in the flow diagram of Figure 3, has two computational aspects. The first part is a linear programming model that maximizes net returns above total costs subject to a set of restrictions specified for period t. The second part is an updating

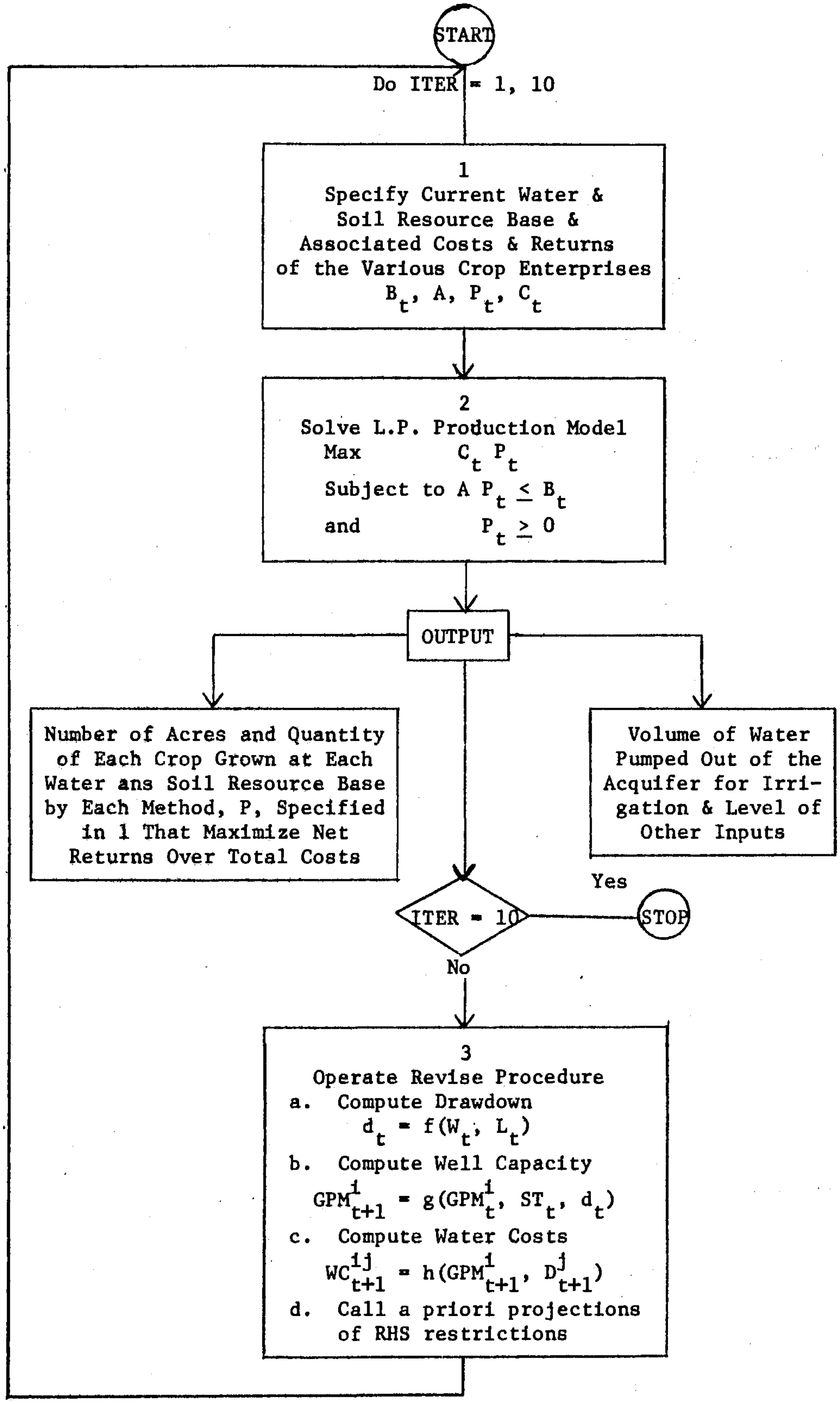

Figure 3. The Recursive Linear Programming Model

process in which changes external to the first part are computed and employed in revising the parameters of the linear programming model for the next period, t + 1. At any production period t the inputs to the model are (1) the soil and water resource base and the appropriate set of production restrictions represented by vector B_t, (2) the various crop enterprises, selling and buying activities represented by matrix P_t, (3) the associated input-output coefficients of the activities in P_t represented by matrix A and (4) the net returns accruing from the activities in P_t represented by vector C_t as shown in Figure 3. The outputs of the model are (1) the number of acres and amount of the various crops grown on each soil and water stratum under different levels of water application, viz. high level, low level and dryland, (2) the volume of water pumped out of the aquifer, (3) the level of other inputs used, and (4) the total net return from all enterprises.

In the second part of the model, several calculations are made to update and specify the parameters of the linear programming model for period t + 1. First, the volume of water used for irrigation in period t is added to an _a priori_ projected water demand for industrial and municipal purposes in that period and adjusted for mean annual recharge. This quantity is denoted as W_t. Then the decline, d_t, in the static water table level at the end of period t is calculated as a function of the net volume of water extracted from the aquifer and the appropriate surface (land) area L, i.e., $d_t = f(W_t, L_t)$. Based on the change in the static water table level, saturated thickness, ST_t^i, and well capacity, GPM_t^i, i = 1, 2, ..., 6, the next period's well capacity of the six saturated thickness classes are computed.[8] Implicitly we have:

$$GPM^{i}_{t+1} = g(GPM^{i}_{t}, ST_{t}, d_{t}).$$

Once these capacities are known and the pump lift, D^{j}_{t}, is updated to D^{j}_{t+1}, ($j = 1, 2, \ldots, 8$) representing the eight pump lift classes, the water cost, WC^{ij}_{t+1}, can be calculated.[8] Implicitly we have:

$$WC^{ij}_{t+1} = h(GPM^{i}_{t+1}, D^{j}_{t+1}).$$

These water costs are used to update the cost of the water buying activities in P_t by revising the appropriate elements of vector C_t. Finally the set of _a priori_ projections are used to revise vector B_t.

When this process is completed the inputs of the production model are updated and the model is ready to generate the production pattern for period $t + 1$. The complete process is iterated for $t = 10$ periods, each period representing a span of ten years. The model is run once for 1965 benchmark conditions by whose results the initial conditions for 1970 are specified. Then $t = 1$ is made to represent the ten year period 1970-1979. When $t = 10$, the calendar year period is 2060-69 and the production has been depicted for a period of one century.

The above discussion explains the general operation of the recursive linear programming production model through time. The following section is devoted to the discussion of the broad assumptions made in specifying and employing the model to generate the solutions.

Two Broad Assumptions

In projecting the long term rates of ground water use from the Central Ogallala Formation, one is faced with a complex interaction of physical, economic, social and political factors that may be impossible to predict. On the physical side, there are several factors that affect the rate of ground water withdrawal including the distribution of precipitation among future years. In periods of prolonged drought farmers may have to dig more wells to obtain sufficient water for their crops thereby accelerating the rate of ground water use. In periods of heavy precipitation irrigators will pump less water, thereby decelerating the rate of ground water use and also recharge may appreciably increase for subsequent periods. Technological breakthroughs in plant breeding, fertilizer applications, pumping and distribution of water may increase the efficiency of production per unit of water used. One may also add breakthroughs in weather control to the list, all of which will result in a decrease in the rate of ground water use per production period. The transfer of water from surplus areas, if it is economically and politically feasible, may entirely alter the importance of ground water in the study area.

On the economic scene, the general state of the economy will dictate whether or not irrigators can borrow the capital they need to expand their operations at a price they can afford to pay. Farmers will continue to expand their irrigation activities as long as their marginal costs of water are equal to or less than their expected marginal returns. Whether marginal costs of ground water will stay less than or equal to their expected marginal returns depends upon a multitude of economic factors that affect both input and output prices, ranging from the level of the interest rate, the wage rate and world commodity prices to the current status of their ground water supply.

On the social and political side are factors such as population growth which increases the demand for food and may induce the expansion of irrigation. The changing pattern or style of life may place a high priority on water use for recreation and the growing concern for maintaining or improving the quality of the environment may mean increased use of water by industry and more public funds diverted for the abatement of pollution, all of which put a strain on the political and economic feasibility of water transfer for irrigation purposes. Government commodity programs and U. S. food exports through commercial channels and government-financed programs affect the demand for agricultural products and the growth of irrigation in the study area.

Indeed, the interplay of all these factors muddles the picture for the future. One can shed some light on it only by looking back at past events and conditioning one's projections for the future on their basis. In order to accomplish this and cut down the problem to a manageable size, some simplifying assumptions need to be made.

As indicated earlier, the study area possesses a substantial amount of irrigable land and ground water with which to irrigate it. Irrigated acres have more than doubled in the first half of the last decade. The problem one faces is how to allow for the rate of irrigation growth in the production model. If one extrapolates past trends, would the production supplied by the study area find an effective demand at prices that can sustain irrigated production at rates of return to the resources so committed in line with those in other sectors of the economy? The recursive production model was run under each of two broad assumptions to answer the first question. The production model is referred to as either Model I or Model II to reflect these two assumptions.

Model I

Model I represents a situation in which future agricultural production in the study area and the U. S. is assumed to be in balance with estimated future demands. For this purpose the U. S. Department of Agriculture's national projections, which are based on such an assumption, were disaggregated to derive the study area's future supply. The national projections

> ...are based upon examination of current relationships and evaluation of foreseeable developments. The major forces considered in the projections are population growth, shifts in consumer demands, industrial and other uses of agricultural commodities; livestock feeding efficiencies and feed ration composition; foreign demand for agricultural products and the advance of technology in the production of crops and livestock.[9]

Since the projections represent an economy where agricultural production is in balance with estimated future demands, the projected national supply of the agricultural commodities can alternatively be viewed as the demand for them. The national projections were made for the years 1980, 2000 and 2020 taking 1959-61 as the base period.

A simple shift share technique was used in disaggregating the national projections to that of the study area. The study area's historic proportional share of the national supply was applied to the projected national production figures. The use of such a simple shift-share disaggregation procedure as discussed above assumes that regional competition will remain the same and the study area will maintain its share of the national supply at the 1965-67 level. Any interpretation of the projected production will have to take into account the significance of this assumption.

These projections were incorporated in the production model as upper limits in the right-hand side, vector B_t. Thus Model I maximized net returns subject to meeting the specified *a priori* production goal projected for the period in question.

Model II

Model II represents a situation in which the study area is allowed to produce more than its historic share of the projected U. S. production, subject to an upper constraint imposed by the maximum rate of irrigation growth possible. If such a restriction were not imposed, the model would irrigate every irrigable acre in the entire study area. The maximum rate of growth of irrigation was computed on the basis of the rate at which the maximum physical limit was being approached in the recent past. An exponential growth model was employed in projecting the number of acres to be irrigated beyond 1965.[10]

The Sequential Decision Model

It is the purpose of this section to develop a sequential decision model that enables one to map the optimum strategy that will maximize the study area's net income from irrigation under various levels of underground water storage for a given planning horizon. Comparing the results of such a model with the rate of ground water withdrawal suggested by the linear programming production model will indicate whether it appears irrigators acting individually will extract water at a rate greater than that indicated optimal by the sequential decision model.

In a closed aquifer where natural recharge is extremely low and ground water mining is practiced the problem of optimal allocation of ground water over time is essentially a problem of choice among the various quantities of water to leave stored in the aquifer at different points in time. The decision of how much water to withdraw in any period t has a direct bearing on how much will be left in storage for the following period t + 1. More important, the decision to withdraw a certain quantity of water not only determines the net income for period t but also influences the per unit cost of water in subsequent periods. The hydrologic relationships dictate that when a quantity of water is pumped out of the aquifer in period t, the water table declines thereby increasing pump lift and decreasing well capacity for period t + 1, a phenomenon which translates to a higher per unit water cost and hence, *ceteris paribus*, lower net return per unit of water used in period t + 1. Thus the net return at any future period is a function of the storage level at that period (which incidentally is a function of the initial storage level and the cumulated withdrawals in the interim periods) and the decision to withdraw W_t quantity of water in that period. The problem is to find the optimal decisions, for all periods in a given planning horizon, which may be defined as those decisions of the rate of ground water withdrawal that will maximize the study area's net income over the entire planning horizon. Since there is an interdependence between decisions and storage levels from period to period, a sequential multi-period decision model is required to map the decision strategy in all the intermediate periods to attain the goal of maximum net return from all withdrawals in the planning horizon. An optimizing technique that is capable of accomodating such a model has been developed by Richard Bellman.[11] The rest of this chapter is concerned with formulating such a decision model and a discussion of the optimizing technique for which Bellman has coined the name "dynamic programming".

The Multi-Stage Sequential Decision Process

The decision process or economic activity is performed in time periods or intervals which are referred to as stages. The multi-stage sequential decision process consists of a series of these stages joined together so that the output of one stage becomes the input to the next.[12]

A stage may represent any span of time suitable for the particular problem under study. For our purposes the economic decision to extract ground water at a certain rate per year will be made for a planning horizon of 100 years subdivided into ten 10-year intervals. Thus a stage refers to a period ten years in length, or our multi-stage process has ten stages in which an economic decision is performed at each stage.

An important concept of the model is the state of the process, which describes the condition of the system at the beginning and end of each stage. In this study the level of underground water at the beginning of a stage is referred to as the input state. The output state is the level of underground water in storage at the end of a stage.

At each stage there exists a set of relevant alternative decisions among which one will be selected as the optimal policy to be carried out in that stage. Here, the decision variable is the annual rate of groundwater withdrawal. The set of alternative decisions contains various quantities of water to be withdrawn annually.

The decision to execute one alternative from the set transforms the condition of the system from an input state at the beginning of the stage into an output state at the end of the stage. In other words, the alternative selected at a particular stage and state of the process dictates the state which the system will occupy in the following stages. This leads to the concept of transition and transition probabilities.

Transition refers to the transformation of a given input state to any output state via a given alternative decision. For any given input state and an alternative decision the output state depends upon the magnitude of the alternative selected and the nature of other variables that affect the state of the system. Considering the nature of these other variables, each alternative decision may transform the given input state to a given output state with certainty or with some degree of uncertainty. If the transformation is known to occur with certainty the process is said to be deterministic, i.e., a given alternative taken in a certain input state has a unique outcome. The transition probability, defined as the probability that a given input state will end up in a certain output state via a selected alternative decision, in the deterministic case is either zero or one. If the process is stochastic any alternative selected has no unique outcome and the transition probabilities take on values from one to zero. (One may find stochastic processes in which some of the transition probabilities are one or zero.) The multi-stage decision process analyzed in this study is assumed deterministic because natural annual recharge is small in relation to the magnitude of the decision variable, the rate of ground water withdrawal, and little is known about its variability. This condition is discussed in Chapter V.

Associated with each transformation is a stage return that accrues to the execution of the policy selected in that stage. The stage return in this study is the total net returns derived from applying the selected quantity of water to irrigated crops in the study area.

Consider the following schematic and mathematical representation of the multi-stage decision model. First define M discrete underground water storage levels S_i, i = 1, 2, ..., M, each level representing a state, and K discrete alternative rates of ground water withdrawal, W_k, k = 1, 2, ..., K. Define P_{ij}^k as the transition probability of the system in transforming from input state i to output state j via alternative decision k. Define R_{ij}^k as the net return accruing from alternative decision k being carried out and the system transiting from input state i to output state j. In reference to a particular stage n, n = 1, 2, ..., N, of the N stage system we have

$S_i(n)$ = input state of the system in the n^{th} stage,

$S_j(n)$ = output state of the system in the n^{th} stage,

$W_i^k(n)$ = k^{th} alternative decision selected as optimal in the n^{th} stage, and

$R_{ij}^k(n)$ = the net return accruing to $W_i^k(n)$.

The Stage Transformation

In general the n^{th} stage transformation of the state of the process may be represented by:

$$S_i(n) = T_{(n-1)}[S_i(n-1), W_i^k(n-1)] \tag{1}$$

Relation (1) indicates that the input state in the n^{th} stage, or alternatively the output state of the $n-1^{th}$ stage, is a function T of the input state in the preceding stage, $S_i(n-1)$, and the optimal decision taken in that stage. In the underground water situation the transformation function can be expressed explicitly by the recursive relation:

$$S_i(n) = S_i(n-1) + A(n-1) - W_i^k(n-1) \tag{2}$$

Where:

$S_i(n-1)$ = level of ground water storage at the beginning of stage (n-1),

$A(n-1)$ = addition to storage by natural recharge during stage (n-1), and

$W_i^k(n-1)$ = quantity of water withdrawn in stage (n-1).

Thus $S_i(n)$ is independent of the latter stages n + 1 through N; it depends only on the decisions made prior to stage n in the stages 1 through n - 1. The series of transformations can be carried back to the initial stage as shown by:

$$\begin{aligned} S_n &= T_{n-1}(S_{n-1}, W^k_{n-1})^{13} \\ &= T_{n-1}[T_{n-2}(S_{n-2}, W^k_{n-2}), W^k_{n-1}] \\ &= T_{n-1}\{T_{n-2}[T_{n-3}(S_{n-3}, W^k_{n-3})], W^k_{n-2}; W^k_{n-1}\} \\ &= T_{n-1}\{T_{n-2}[T_{n-3}, \ldots[T_1(S_1, W^k_1)], W^k_2], \ldots, W_{n-1}\} \end{aligned} \tag{3}$$

The Stage Return and the Optimization Principle

The stage return at any stage n is given by:

$$R_i^k(n) = f_n[S_i(n), W_i^k(n)] \tag{4}$$

which says that the stage return, $R_i^k(n)$, is a function of the input state S_i at the beginning of the stage and the k^{th} alternative decision selected in that stage. In general, for the N stage system we have a sequence of stage returns given by the criterion function:

$$F[S_i(1),\ S_i(2),\ \ldots,\ S_i(N);\ W_i^k(1),\ W_i^k(2),\ \ldots,\ W_i^k(N)] \qquad (5)$$

The optimization problem, the solution of which is the purpose of the multi-stage sequential decision model, now becomes one of choosing the $W_i^k(n)$ at each stage n so as to maximize the criterion function F over all stages one through N for the entire planning horizon. An optimal policy function $W(W_i^k(1),\ W_i^k(2),\ \ldots,\ W_i^k(N))$ specifies the optimal decision for all combinations of input states, S_i, and stages n which will result in the optimization of the criterion function F.

In order to apply the dynamic programming technique to solve the optimization problem, the criterion function F has to display the property of a Markovian dependence which states that:

> After any number of decisions say k, we wish the effect of the remaining N-k stages of the decision process upon the total returns to depend only upon the state of the system at the end of the k^{th} decision and the subsequent decisions.[14]

In other words, once the input state is specified at each stage, the decision taken in that stage is independent of the decisions taken in earlier stages so that only the decision in the current and the subsequent remaining stages affect the total net returns. In the case of the optimum inter-temporal allocation of ground water the storage level at the beginning of each stage must absorb all the influences of the decisions taken heretofor. Henceforth, the total net return is affected by the choice of the rate of ground water withdrawal in the current and subsequent stages.

This property of a Markovian dependence enables one to decompose the criterion function F into a sum of separate individual stage returns and we have:

$$f_1\ [S_i(1),\ W_i^k(1)] + f_2\ [S_i(2),\ W_i^k(2)] + \ldots + f_N\ [S_i(N),\ W_i^k(N)].$$

Given the initial state of the system as S_1 and the number of stages as N, the maximization problem can now be stated as

$$f_N(S_1) = \max_{W_n^k} [f_1(S_1,\ W_1^k) + f_2(S_2,\ W_2^k) + \ldots + f_N(S_N,\ W_N^K)] \tag{6}$$

Due to the separability of the criterion function relation (6) can be restated as

$$f_N\,(S_1) = \max_{W_1^k} f_1(S_1,\ W_1^k) + \max_{W_2^k} \max_{W_3^k} \ldots \max_{W_N^k} [f_2(S_2,\ W_2^k + f_3(S_3,\ W_3^k) + \ldots + f_N(S_N,\ W_N^k)]. \tag{7}$$

Note the expression:

$$\max_{W_2^k} \max_{W_3^k} \ldots \max_{W_N^k} [f_2(S_2,\ W_2^k) + f_3(S_3,\ W_3^k) + \ldots + f_N(S_N,\ W_N^k)]$$

represents the total net return from an (N-1)-stage decision process as S_2 the initial state of the system. Hence we can write it as

$$f_{N-1}(S_2) = \max_{W_2^k} \max_{W_3^k} \ldots \max_{W_N^k} [f_2(S_2,\ W_2^k) + f_3(S_3,\ W_3^k + \ldots + f_N(S_N,\ W_N^k)]. \qquad N \geq 2 \tag{8}$$

Substituting this result in relation (7) it simplifies to:

$$f_N(S_1) = \max_{W_1^k} [f_1(S_1,\ W_1^k) + f_{N-1}(S_2)] \tag{9}$$

using the transformation equation (3), $S_2 = T_1(S_1, W_i^k)$ and we can write (9) as

$$f_N(S_1) = \max_{W_i^k} \{f_1(S_1, W_1^k) + f_{N-1}[T_1(S_1, W_1^k]\}. \tag{10}$$

Relation (1) gives the recursive optimization equation connecting all members of the sequence $f_N(S_1)$. It can also be derived from Bellman's principle of optimality which states that:

> An optimal policy has the property that whatever the initial state and the initial decision, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.[15]

The first optimal decision W_1^k yields the return $f_1(S_1, W_1^k)$ transforming the state of the process from S_1 into $T_1(S_1, W_1^k)$ and also reducing the number of stages from N to N-1. The optimal decision for the remaining N-1 stages and the state resulting from the first decision is:

$$\max_{W_1^k} \{f_{N-1}[T_1(S_1, W_1^k)]\}.$$

Combining this with the first decision we have

$$f_N(S_1) = \max_{W_1^k} \{f_1(S_1, W_1^k) + f_{N-1}[T_1(S_1, W_1^k)]\} \tag{11}$$

which is exactly the same as relation (9).

The above formulation is centered around S_1 as the only input state or initial condition of the system. Since there are S_i, $i = 1, 2, \ldots,$ M, possible input states at each stage relation (9) should be written to include all the possible inputs of the system. Doing so results in

$$f_N(S_i) = \max_{W_i^k} \{f_1(S_i(1), W_i^k(1)) + f_{N-1}[T_1(S_i(1), W_i^k(1))]\}. \tag{12}$$

At this point we shall introduce into the recursive optimization equation (1) the interest rate, r, in order to discount to a comparable level the net return streams generated by the sequential decisions at different time periods as the system moves from stage to stage, (2) the transition probabilities to reflect the deterministic or stochastic nature of the process and (3) the explicit transformation function to replace its implicit counterpart. Thus, we have for any stage n and any input state i

$$f_n(S_i) = \operatorname*{Max}_{W_i^k(n)} \{f_n[S_i(n),\ W_i^k(n)] + (1 + r)^{-1} \cdot \sum_{j=1}^{M} P_{ij}^k \cdot f_{n-1} [S_i(n-2) + A(n) - W_i^k(n-2)]\}, \tag{13}$$

$i = 1, 2, \ldots, M$; $n = 0, 1, 2, \ldots, N$. Substituting the stage return $R_i^k(n)$ for $f_n[S_i(n),\ W_i^k(n)]$, β for $(1 + r)^{-1}$, S_j for $[S_i(n-2) + A(n) - W_i^k(n-2)]$ and $\max_k$ for $\operatorname*{Max}_{W_i^k(n)}$ we have

$$f_n(S_i) = \operatorname*{Max}_{k} [R_i^k(n) + \beta \cdot \sum_{j=1}^{M} P_{ij} \cdot f_{n-1} S_j], \tag{14}$$

$i = 1, 2, \ldots, M$; $n = 0, 1, 2, \ldots, N$.

Relation (14) may be interpreted to say that the expected present value of an N-n stage process under an optimal policy is the maximum sum of the expected net return accruing to the decision in stage n and the discounted expected net returns from the remaining n-1 stages, provided an optimal policy will be carried out in the remaining n-1 stages.

The recursive solution of equation (14) starting from n = 1 and continuing through n = N yields the optimal N-stage returns. Since we are dealing in the future and we wish to maximize the expected discounted total net return, such an optimization can be carried only from the future to the present.[16] Computationally, the procedure involves starting with the last stage of the planning horizon treated as one-stage process and carrying out the maximization on k for all S_i. Then the second stage from the last is taken up as a two-stage process using the results of the one-stage process to carry out the maximization on k for all S_i. Then a three-stage, four-stage, ..., n-stage process is treated yielding the maximum expected discounted net return. Stated formally, the backward iterative solution, carried from the future to the present, for each state i = 1, 2, ..., M becomes:

$$f_i(N) = \underset{k}{\text{Max}} \left[R_i^k(N) + \beta \cdot \sum_{j=1}^{M} P_{ij} \cdot f_j(N+1)\right]$$

$$f_i(N-1) = \underset{k}{\text{Max}} \left[R_i^k(N-1) + \beta \cdot \sum_{j=1}^{M} P_{ij} \cdot f_j(N)\right]$$

$$\vdots$$

$$f_i(n) = \underset{k}{\text{Max}} \left[R_i^k(n) + \beta \cdot \sum_{j=1}^{M} P_{ij} \cdot f_j(n+1)\right]^{17}$$

$$\vdots$$

$$f_i(2) = \underset{k}{\text{Max}} \left[R_i^k(2) + \beta \cdot \sum_{j=1}^{M} P_{ij} \cdot f_j(3)\right]$$

$$f_i(1) = \underset{k}{\text{Max}} \left[R_i^k(1) + \beta \cdot \sum_{j=1}^{M} P_{ij} \cdot f_j(2)\right]$$

i = 1, 2, ..., M; k = 1, 2, ..., K.

Since N+1 is outside the system, a terminal value of zero is assigned to $f_j(N+1)$ so that the recursive solution can be stated as:

$$f_i(N) = \underset{k}{\text{Max}}\ R_i^k(N).$$

For a solution to each $f_i(N)$ for the next iteration, $f_j(n-1)$, n = 0, 1, 2, ..., N, is supplied by the solution for $f_i(n)$ in the current iteration. For any period having n-stages remaining in the planning horizon, the optimal strategy for each of possible M initial input states is given by the function $W[W_i^k(n), W_i^k(n-1), \ldots, W_i^k(2), W_i^k(1)]$ which is a set of those alternative ground water withdrawal rates that maximize the sum of discounted expected net returns at each remaining stage in the planning horizon. Associated with the function W is the function $F[f_i(n)\ f_i(n-1), \ldots, f_i(2), f_i(1)]$ which gives the corresponding sum of maximum discounted expected net return.

In Figure 4,[18] given the initial, 1970, level of ground water storage as state one (S_1), stage one represents the first ten-year period of the planning horizon in which the decision on the optimal rate of ground water withdrawal, $W_i^k(1)$, is made. $R_i^k(1)$ is the net return that accrues to the optimal decision, $W_i^k(1)$, in stage one. The execution of $W_i^k(1)$ transforms the state of the system into an output state, $S_j(1)$, which becomes the input state, $S_i(2)$, in the second stage (1980-89), where the optimal decision, $W_i^k(2)$, is selected and the system is transformed to an output state, $S_i(3)$. The process continues in a similar fashion from stage to stage until the final stage, N=10, is reached.

This chapter has presented the analytical models that will be used to achieve the major objectives of the study. The input data for the recursive linear programming production models is developed in the following chapter.

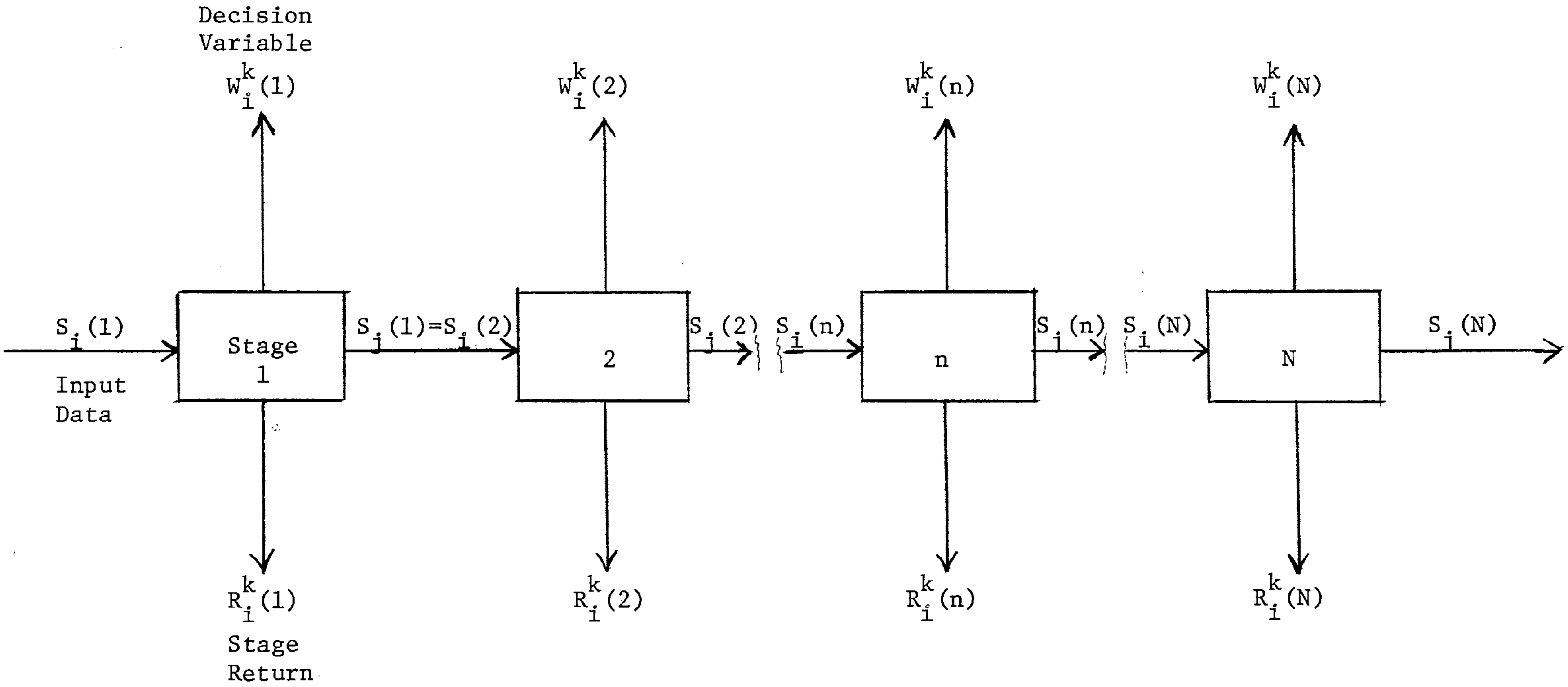

Figure 4. The Multistage Sequential Decision Model

FOOTNOTES

[1] James M. Henderson, "The Utilization of Agricultural Land: A Theoretical and Empirical Inquiry", *Review of Economics and Statistics*, Vol. 41, No. 3 (August, 1959), pp. 242-259.

[2] Richard H. Day, *Recursive Programming and Production Response*, North Holland Publishing Co. (Amsterdam, 1963).

[3] Richard H. Day, "An Approach to Production Response", *Agricultural Economics Research*, Vol. 14, No. 4 (October, 1962), and W. Neill Schaller, "A National Model of Agricultural Production Response", *Agricultural Economics Research*, Vol. 20, No. 2 (April, 1968).

[4] G. E. Frick and R. A. Andrews, "Aggregation Bias and Four Methods of Summing Farm Supply Functions", *Journal of Farm Economics*, Vol. 47, No. 3 (August, 1965), pp. 696-700, and R. Barker and R. F. Stanton, "Estimation and Aggregation of Firm Supply Functions", *Journal of Farm Economics*, Vol. 47, No. 3 (August, 1965), pp. 701-712.

[5] Jerry A. Sharples, "The Representative Farm Approach to Estimation of Supply Response", *American Journal of Agricultural Economics*, Vol. 51, No. 2 (May, 1969), pp. 353-361.

[6] Ibid.

[7] Richard H. Day, "On Aggregating Linear Programming Models of Production", *Journal of Farm Economics*, Vol. 45, No. 4 (November, 1963), pp. 797-813.

[8] See Chapter III, p. 41 for saturated thickness and depth to water classes.

[9] U. S. Department of Agriculture, *Preliminary Projections of Economic Activity in the Agricultural, Forestry and Related Economic Sectors of the United States and Its Water Resource Regions, 1980, 2000 and 2020*. For use of the Water Resources Council and Cooperating Agencies for Comprehensive River Basin Planning. Prepared by the Economic Research and Forest Service (August, 1967), pp. x and 1.

[10] The exponential model is discussed in Chapter III.

[11] Richard Bellman, *Dynamic Programming*, Princeton University Press (Princeton, 1957).

[12] George L. Nemhauser, *Introduction to Dynamic Programming*, John Wiley and Sons Inc. (New York, 1966), p. 26.

[13] The subscript i on the S term and the parenthesis around the stage numbers have been dropped to simplify the notation.

[14] Richard Bellman, Adaptive Control Processes: A Guided Tour, Princeton University Press (Princeton, 1961), p. 54.

[15] Ibid, p. 57.

[16] A. Kaufman, "Graphs, Dynamic Programming, and Finite Games", Mathematics in Science and Engineering, Vol. 36, Academic Press (New York, 1961), p. 107.

[17] Note that n refers to the number of stages remaining in the planning horizon. Hence, n = 1 refers to the last stage N, n = 2 refers to the second last stage N-1, etc.

[18] Nemhauser, p. 17.

CHAPTER III

THE INPUT DATA FOR THE RECURSIVE LINEAR PROGRAMMING MODELS

The input data used to specify the two RLP production models and the assumptions used in developing the data are presented in this chapter. The computations made in updating the parameters related to the water variable are also discussed. For any given production period the basic data for Model I and Model II are the same. The activities represented by matrix P_t and the input-output coefficients denoted by matrix A are identical in both models.[1] The objective function given by C_tP_t is identical in both models only for the initial 1965-69 production period. As the two models withdraw water from the aquifer at different rates water costs change in different magnitudes in the two models from one production period to the next. Thus some elements of C_t will have different values in Model I and Model II for any production period other than the 1965-69 period. The elements of the right hand side vector, B_t, are composed of two types of restrictions. The restrictions that delimit the water and soil resource base available for crop production have the same value in both models as they are fixed quantities to the study area. The rest of the elements in vector B_t are different in the two production models. The following discussion indicates differences in the parameters used in the two models.

The Soil and Water Resource Base

The first step in depicting the irrigated crop production pattern is to inventory the soil and water resources in the study area and stratify them according to their common characteristics.

The Soil Classification Scheme

It was necessary to classify the soils of the study area into homogeneous groups in order to relate the distribution of irrigable and non-irrigable soils to the water resources throughout the study area. The Soil Conservation Service (SCS) county soil surveys provided the basic data for this purpose. Such surveys were not available in published form for the counties of Baca in Colorado, Grant, Haskell, Gray and Meade in Kansas and all counties in Texas except Hansford. The data for these counties were obtained from field work sheets in the county SCS offices. County SCS personnel were also consulted to verify the classification scheme.

The soils of each county were first divided into irrigable and non-irrigable groups using the irrigated capability units as the criterion of classification. The irrigable soils were further subdivided into clay A, clay B, sand A, and sand B groups. The clay groups includes all silty loam, clay loam and silty clay loam soils, while the sand category includes all fine sandy loam and loamy fine sand soils.

The clay A soils are deep, nearly level (zero to three percent slope), moderately fine to medium textured and well drained soils. Soils in the clay B subdivision are moderately fine to medium textured that are characterized by management limitations such as poor drainage, erosion and moderate to steep slopes.

The sand A group consists of deep, well drained and moderately coarse textured soils which are nearly level to gently sloping. Soils in the sand B subdivision are deep, coarse textured with moderately fine to moderately coarse subsoils. They have the same type of management limitations as the clay B group, and range in slope from nearly level to moderately steep.

These soil groups were identified and plotted on the map of each county. Table III summarizes the distribution of each soil group in the study area. Due to their slope and management characteristics all A soils are assumed to be suitable for furrow irrigation and all B soils are assumed to be best suited for sprinkler irrigation.

TABLE III

DISTRIBUTION OF SOIL TYPES IN THE STUDY AREA

Soil Type	No. of Acres	No. of Acres	Percent of Total	Percent of Irrigable Soils
Non-irrigable	3,108,423		27.88	
Irrigable	8,040,915		72.12	100.00
Clay A		5,366,204		66.74
Clay B		801,296		9.96
Sand A		897,170		11.16
Sand B		976,245		12.14
TOTAL	11,149,338		100.00	

The Soil and Water Resource Situation Strata

Hydrologic maps of each county in the study area were used to inventory the water resource. Two maps for each county provided the information required. The saturated-thickness map indicated the number of feet of water saturated material in the aquifer. The depth-to-water map indicated the vertical distance from the ground surface to the static water table. By superimposing the depth-to-water map on the saturated-thickness map and delineating the area between two adjacent depth-to-water contour lines that lies between two adjacent saturated-thickness contours, a stratified water resource inventory was generated. The stratification involved (1) six classes of saturated thickness ranging from zero to 600 feet by 100-foot class intervals and (2) eight classes of depth to water ranging from less than 50 feet to 400 feet by 50-foot class intervals. Thus a matrix of six by eight water resource strata or 48 water resource situations were defined. The class intervals chosen for the saturated-thickness and depth-to-water were the least common intervals of the contours plotted on the hydrologic maps available for the area. The stratified water resource map was superimposed on the soil inventory map. The area occupied by the various soil groupings falling in the different water resource strata was planimetered to generate the entire soil and water resource base inventory. Table IV presents the measured acreage of each soil group by water stratum.

Excluding the non-irrigable soils, which are mostly composed of roughs and breaks along the streams and used for rangeland, there are 32 soil and water resource situations in each of the six saturated thickness classes. This implies a total of 192 soil and water resource

TABLE IV

INVENTORY OF THE SOIL AND WATER RESOURCE BASE

Saturated Thickness	Depth to Water	Clay A Acres	Clay B Acres	Sand A Acres	Sand B Acres	Non Irrigable Acres	Total Acres	Percent
Under 100 ft.								
	Under 50 ft.	109,307	37,799	24,694	38,339	279,716	489,855	4.39
	51-100 ft.	327,401	58,149	58,066	86,754	289,497	819,867	7,35
	101-150 ft.	295,892	14,071	38,564	64,021	46,470	459,018	4.12
	151-200 ft.	294,876	13,284	46,803	48,844	133,981	537.788	4.82
	201-250 ft.	78,469	12,262	14,355	18,606	28,016	151,708	1.36
	251-300 ft.	47,142	12,473	8,423	11,614	20,855	100,507	0.90
	301-350 ft.	17,223	6,923	5,725	8,354	11,014	49,239	0.44
	Over 350 ft.	9,916	4,088	6,382	9,313	7,733	37,432	0.35
	Subtotal	1,180,226	159,049	203,012	285,845	817,282	2,645,414	23.73
101-200 ft.								
	Under 50 ft.	64,404	23,923	20,742	42,163	159,732	310,964	2.79
	51-100 ft.	124,530	49,654	32,080	107,839	223,056	537,159	4.82
	101-150 ft.	182,723	35,932	22,416	25,511	92,988	359,570	3.22
	151-200 ft.	306,505	22,995	27,836	34,708	215,069	607,113	5.54
	201-250 ft.	240,957	22,653	16,355	19,432	58,982	358,379	3.21
	251-300 ft.	140,565	17,526	20,576	32,716	43,936	255,319	2.29
	301-350 ft.	40,830	5,576	6,012	10,398	31,531	94,347	0.85
	Over 350 ft.	4,475	1,066	1,827	3,167	15,168	25,703	0.23
	Sub total	1,104,989	179,325	147,844	275,934	840,462	2,548,554	22.86
201-250 ft.								
	Under 50 ft.	49,217	29,403	4,630	11,575	120,868	215,693	1.94
	51-100 ft.	155,084	68,119	39,663	56,401	313,447	632,714	5.68
	101-150 ft.	194,715	56,813	39,481	11,181	121,663	423,853	3.80
	151-200 ft.	550,915	42,688	40,368	17,154	148,625	799,750	7.17
	201-250 ft.	240,708	22,483	12,690	3,979	49,480	329,340	2.95
	251-300 ft.	122,604	9,471	24,803	7,875	50,066	214,759	1.93
	301-350 ft.	98,096	7,029	17,978	2,082	85,335	210,520	1.89
	Over 350 ft.	22,639	1,768	2,037	---	16,399	42,843	0.38
	Subtotal	1,433,978	237,774	181,650	110,247	905,883	2,869,472	25.74

TABLE IV (Continued)

Saturated Thickness	Depth to Water	Clay A Acres	Clay B Acres	Sand A Acres	Sand B Acres	Non Irrigable Acres	Total Acres	Percent
301-400 ft.								
	Under 50 ft.	69,487	14,252	13,239	1,483	47,201	145,662	1.31
	51-100 ft.	174,692	35,460	28,269	23,687	76,678	338,786	3.04
	101-150 ft.	218,434	28,251	29,058	22,252	70,049	368,044	3.30
	151-200 ft.	562,963	76,836	71,451	35,406	132,675	879,331	7.89
	201-250 ft.	89,954	15,060	4,218	2,096	21,686	133,014	1.19
	251-300 ft.	29,873	4,901	141	---	965	35,880	0.32
	301-350 ft.	30,132	5,419	2,573	512	12,824	51,460	0.46
	Over 350 ft.	8,902	1,803	380	78	2,114	13,277	0.12
	Subtotal	1,184,437	181,982	149,329	85,514	364,192	1,965,454	17.63
401-500 ft.								
	Under 50 ft.	2,236	1,799	---	418	25,559	30,012	0.27
	51-100 ft.	54,314	13,491	16,962	13,456	19,263	117,486	1.05
	101-150 ft.	117,557	5,927	58,480	72,732	44,233	298,929	2.68
	151-200 ft.	101,764	4,433	27,866	39,693	29,677	203,433	1.82
	201-250 ft.	13,052	3,540	---	---	1,883	18,475	0.17
	251-300 ft.	14,010	2,791	---	---	1,584	18,385	0.17
	301-350 ft.	15,287	3,052	---	---	1,730	20,069	0.18
	Over 350 ft.	5,497	1,516	---	---	801	7,814	0.07
	Subtotal	323,717	36,549	103,308	126,299	124,730	714,603	6.41
Over 500 ft.								
	Under 50 ft.	15,945	289	7,458	3,694	5,504	32,890	0.30
	51-100 ft.	33,509	---	22,306	14,037	9,496	79,348	0.71
	101-150 ft.	70,493	55	50,966	68,512	26,120	216,646	1.94
	151-200 ft.	17,608	1,742	31,297	6,163	13,898	70,708	0.63
	201-250 ft.	294	910	---	---	206	1,410	0.01
	251-300 ft.	223	690	---	---	157	1,070	0.01
	301-350 ft.	785	2,431	---	---	533	3,769	0.03
	Over 350 ft.	---	---	---	---	---	---	---
	Subtotal	138,857	6,617	112,027	92,406	55,934	405,841	3.63
TOTAL						3,108,423	11,149,338	100.00

situations for the entire study area. The number of acres in each of the 192 soil and water resource situations constitute the land base on which the entire crop production activities take place in the study area. These 192 acreages are entered as right hand side restrictions in the B_t vector of both Model I and Model II defining the maximum supply of the land resource available for crop production in the study area.

The Volume of Water in Storage

The quantity of ground water theoretically available for pumping is determined by the hydrologic properties of the aquifer. This quantity can be computed using the formula:

$$V = \sum_{k=1}^{6} A_k \cdot h_k \cdot S,$$

Where:

$k = 1, 2, \ldots, 6$ represents the k^{th} saturated thickness indicated in Table IV,

A_k = surface area associated with the k^{th} saturated thickness class in acres,

h_k = the midpoint of the k^{th} saturated thickness class in feet, and

S = the coefficient of storage.

Following Beck, et. al., in Colorado, Gutentag, et. al., in Kansas, Sapik in Oklahoma and Buchanan in Texas, a coefficient of storage of 0.15 was employed in computing the volume of water available for pumping in the Central Ogallala Formation.[2] This quantity was estimated to be 369,663,804 acre feet in 1965. Table V summarizes the distribution of the available water in storage by saturated-thickness and depth-to-water strata in both absolute and relative terms. The distribution of water in the aquifer is skewed in favor of the saturated-thickness classes with less irrigable surface area. While the first two saturated thickness classes (0-100 feet and 101-200 feet) comprise 39.24 percent of the total land area, and 43.98 percent of the total irrigable land, they have only 20.88 percent of the total water supply in storage. On the other hand, while the two deepest saturated thickness classes (401-500 feet and >500 feet) comprise 10.04 percent of the total land area, and 11.69 percent of the total irrigable acres, they have 22.11 percent of the total water supply in storage. As irrigation continues to develop and overdraft increases, the shallow saturated-thickness classes probably will be the first to be adversely affected by the declining water table. The skewness of the water supply distribution implies that about 44 percent of the total irrigable acres will experience rapidly increasing costs of obtaining water from the aquifer as the water table declines. The third and fourth saturated-thickness classes (201-300 feet and 301-400 feet) constitute 43.37 percent of the total land area, and 44.33 percent of the total irrigable acres and have 57.01 percent of the total water supply in storage. This situation coupled with the fact that of the 57.01 percent figure the 45.61 portion lies at an initial depth of 200 feet or less implies that irrigated activity may be sustained for a prolonged period of time in areas where these saturated-thicknesses dominate.

TABLE V

WATER RESOURCES INVENTORY OF STUDY AREA, 1965

Initial Saturated Thickness	Item	Depth to Water (Pump Lift)								
		<50'	51'-100'	101'-150'	151'-200'	201'-250'	251'-300'	301'-350'	>350'	Total
0'-100'	No. of Acres	489,855	819,867	459,018	537,788	151,708	100,507	49,239	37,432	2,645,414
	% of Total	4.39	7.35	4.12	4.82	1.36	0.90	0.44	0.35	23.73
	Ac. Ft. in Storage	3,673,912	6,150,352	3,442,635	4,033,411	1,137,810	753,803	369,291	280,740	19,841,954
	% of Total	.99	1.66	0.94	1.09	0.31	0.20	0.10	0.08	5.37
101'-200'	No. of Acres	310,964	537,159	359,570	607,113	358,379	255,319	94,347	25,703	2,548,554
	% of Total	2.79	4.82	3.22	5.45	3.21	2.29	0.85	0.23	22.86
	Ac. Ft. in Storage	6,996,690	12,086,079	8,090,324	13,660,044	8,063,527	5,744,678	2,122,807	578,318	57,342,467
	% of Total	1.89	3.27	2.19	3.70	2.18	1.55	0.57	0.16	15.51
201'-300'	No. of Acres	215,693	632,714	423,583	799,750	329,340	214,759	210,520	42,843	2,869,472
	% of Total	1.94	5.68	3.80	7.17	2.95	1.93	1.89	0.38	25.74
	Ac. Ft. in Storage	8,088,488	23,726,776	17,599,724	28,954,987	12,350,250	8,053,463	7,894,500	1,606,612	108,274,800
	% of Total	2.19	6.42	4.76	7.83	3.34	2.18	2.14	0.43	29.29
301'-400'	No. of Acres	145,662	338,786	368,044	879,331	133,014	35,880	51,460	13,277	1,965,454
	% of Total	1.31	3.04	3.30	7.89	1.19	0.32	0.46	0.12	17.63
	Ac. Ft. in Storage	7,647,255	17,786,266	18,622,760	46,165,088	6,983,235	1,883,700	2,701,650	697,042	102,486,996
	% of Total	2.07	4.81	5.04	12.49	1.88	0.51	0.73	0.19	27.72
401'-500'	No. of Acres	30,012	117,486	298,929	203,433	18,475	18,385	20,069	7,814	714,603
	% of Total	0.27	1.05	2.68	1.82	0.17	0.17	0.18	0.07	6.41
	Ac. Ft. in Storage	2,025,810	7,930,305	20,177,708	13,731,727	1,247,063	1,240,988	1,354,658	527,445	48,235,704
	% of Total	0.55	2.14	5.46	3.71	0.34	0.34	0.37	0.14	13.05
>500'	No. of Acres	32,890	79,348	216,646	70,708	1,410	1,070	3,769	—	405,841
	% of Total	0.30	0.71	1.94	0.63	0.01	0.01	.03	—	3.63
	Ac. Ft. in Storage	2,713,425	6,546,210	17,873,295	5,833,410	116,325	88,275	310,943	—	33,481,883
	% of Total	0.73	1.77	4.84	1.58	0.03	0.02	0.08	—	9.06
Total	No. of Acres	1,225,076	2,525,360	2,126,060	3,098,123	992,326	625,920	429,404	127,069	11,149,338
	% of Total	11.00	22.65	19.06	27.78	8.89	5.62	3.85	1.15	100.00
	Ac. Ft. in Storage	31,145,580	74,225,988	85,806,446	112,378,667	29,898,210	17,764,907	14,753,849	3,690,157	369,663,804
	% of Total	8.42	20.08	23.22	30.40	8.09	4.80	3.99	1.00	100.00

Crop Enterprise Activities

In both models the entire study area is programmed to produce only those crops that are currently being irrigated in significant quantities. Implicitly the assumption is that these crops will continue to be the principal irrigated crops in the study area in future years. Since the production of barley, oats and native pasture are almost exclusively dryland activities, they do not affect water use and therefore are left out of the model in order to reduce the size of the programming matrix. However, as the total cropland available includes land resources on which such activities take place they were represented by a single opportunity cost activity using the dryland net return on barley as the best alternative. The irrigated crop enterprises selected for production are grain sorghum, wheat, corn grain, corn silage, alfalfa, sugar beets, cotton and soybeans. The data in Table XXXIII Appendix C, indicate cotton is a minor crop and is only produced in the Texas portion of the study area. Sugar beets are produced in Colorado and Kansas. Soybeans are not grown in the Colorado and Oklahoma portions. All of the other crops are produced throughout the study area. Corn grain, soybeans, corn silage and sugar beets are assumed to be produced only with irrigation, while alfalfa hay, sorghum grain, wheat and cotton are assumed to be produced both under dryland and irrigation. Two levels of water application are provided for all crops except soybeans and sugar beets which have only one rate of water application. The levels of irrigation for each crop, the corresponding yields, cost and returns are shown in the enterprise budgets used for the linear programming production model in Tables XXXV-XLII Appendix E. The budgets used for alfalfa, corn grain, sorghum grain, wheat, silage and soybeans are those typical for the area around the Oklahoma Panhandle and are considered representative of the study area. Farm management specialists for the area were consulted on the use of these budgets. The budget for cotton was adopted from studies for the high plains of Texas and western Oklahoma. The budget for sugar beets was adopted from studies in Colorado and Kansas.

The Quantity and Distribution of Crop Production in the Study Area

The Quantity of Crops Produced: Model I

It has been mentioned in Chapter II that Model I's production of crops is limited to the study area's historic share of the projected national supply. Supply of crops projected by the USDA for the years 1980, 2000 and 2020 is based on the 1959-61 average supply. In applying the shift share technique, first the study area's proportional share of the national supply in the base period, 1959-61, was computed for the eight irrigated crops. Then its proportional share for 1965-67, the period of most recent complete observation, was computed. The comparison revealed that the study area has made a slight gain in its share of national supply in the feed and feed grain commodities and that it has lost in the production of wheat, reflecting the recent shift to increased cattle production and commercial feedlot operations in the area. Table VI summarizes the magnitude and direction of the shifts. Grain sorghum gained about 3.5 percentage points in the study area's share of the national supply, silage gained about one-tenth of a percent and wheat lost about 1.2 percentage points. All other crops made a slight gain. The 1965-67 average study area's share of the national

TABLE VI

STUDY AREA'S SHARE OF THE U.S. NATIONAL SUPPLY OF SELECTED IRRIGATED CROPS, AVERAGE 1959-61 AND 1965-67

		1959-61 Av.			1965-67 Av.			
Crop	Unit	(1) Study Area Supply	(2) U.S. Supply	(3) (1)÷(2)	(4) Study Area Supply	(5) U.S. Supply	(6) (4)÷(5)	(7)[1] (6)-(3)
Grain Sorghum	bu.	32,314,096	551,609,000	0.058558	66,861,059	717,769,000	0.093151	+0.034593
Wheat	bu.	52,732,092	1,271,086,000	0.041480	40,902,310	1,383,888,000	0.029556	-0.011924
Corn Grain	bu.	1,642,135	3,743,597,000	0.000445	4,712,654	4,307,964,000	0.000953	+0.000659
Silage	tons	433,429	75,785,990	0.005867	697,654	100,558,000	0.006964	+0.001097
Alfalfa	tons	45,235	65,730,000	0.000688	70,432	73,947,667	0.000953	+0.000265
Sugar Beets	tons	48,338	17,046,660	0.002836	111,542	20,208,667	0.005519	+0.002683
Cotton	bales	1,013	14,382,666	0.000070	1,846	10,667,667	0.000173	+0.000103
Soybeans	bu.	16,330	589,257,300	0.000028	293,254	915,596,666	0.000320	+0.000292

[1] Column (7) shows the change in area study's share of the national supply between the two periods.

Source: Computed from U.S. Department of Agriculture, Agricultural Statistics, 1959, 1960, 1961, 1965, 1966, 1967, U.S. Government Printing Office (Washington) and U.S. Department SRS (Colorado, Kansas, Oklahoma, and Texas) Crop and Livestock Reporting Service, reports for 1959, 1960, 1961, 1965, 1966, and 1967.

supply was used to disaggregate the national projections in order to reflect these changes. Table VII presents the supply projection both for the U. S. and the study area. All projections except those for 1980, 2000 and 2020 are either linear interpolations or linear extrapolations. Since one iteration of the production model represents the annual production of a period of ten years the projected supply restrictions employed in Model I are those of the midpoint years, i.e., the 1975 projection is used for the period 1970-1979, the 1985 projection is used for the period 1980-1989, etc.

The Distribution of Production in the Study Area: Model I

Since the production model's objective is to maximize net returns it is conceivable that it will attempt to produce the crops on the clay loam A type soils that lie in deep saturated-thickness and shallow depth-to-water resource situations. In order to prevent such a happening in Model I it is assumed that irrigated crop production is distributed among the 48 water resource situations according to the weight each one carries with respect to the total number of irrigable acres in the study area. These weights were calculated using the following formula:

$$W_{km} = \frac{a_{km}}{A}$$

Where:

$k = 1, 2, \ldots, 6$, represents the k^{th} saturated-thickness class,

$m = 1, 2, \ldots, 8$, represents the m^{th} depth-to-water class,

W_{km} represents the weight for water resource situation (k, m),

TABLE VII

PROJECTED PRODUCTION OF THE PRINCIPAL IRRIGATED CROPS IN THE STUDY AREA AND THE U.S. 1970-2025[1]

Years	Grain Sorghum		Wheat		Corn Grain		Silage		Alfalfa		Sugar Beets[2]		Cotton		Soy Beans	
	Study Area	U.S.	Study Area	U.S.	Study Area	U.S.	Study Area	U.S.	Study Area	U.S.	Study Area	U.S.	Study Area	U.S.	Study Area	U.S.
	1,000 bu.		1,000 bu.		1,000 bu.		1,000 tons		1,000 tons		1,000 tons		1,000 bales		1,000 bu.	
1965-67 (average)	66,861	717,769	40,902	1,383,888	4,711	4,307,964	698	100,558	70	73,948	112	20,209	1.8	10,668	293	915,597
1970	72,963	783,275	45,727	1,547,125	5,022	4,550,500	723	104,174	78	81,506	122	22,076	2.2	12,725	331	1,033,364
1975	79,065	848,780	50,551	1,710,362	5,290	4,793,036	748	107,790	85	89,065	132	23,943	2.6	14,782	369	1,151,132
1980	85,167	914,286	55,376	1,873,600	5,558	5,035,572	773	111,405	92	96,623	142	25,810	2.9	16,840	406	1,268,900
1985	95,230	1,022,322	57,252	1,937,075	5,926	5,369,036	831	119,742	98	103,853	153	27,677	3.0	17,528	427	1,334,400
1990	105,294	1,130,357	59,128	2,000,550	6,294	5,702,501	889	128,078	106	111,084	163	29,545	3.2	18,217	448	1,399,900
1995	115,358	1,238,393	61,004	2,064,025	6,662	6,035,965	946	136,415	113	118,314	173	31,412	3.3	18,905	469	1,465,400
2000	125,421	1,346,429	62,880	2,127,500	7,032	6,371,429	1,004	144,751	120	125,544	184	33,279	3.4	19,594	491	1,531,900
2005	139,228	1,494,643	65,327	2,210,275	7,466	6,764,287	1,075	154,977	128	134,418	204	37,000	3.5	20,458	517	1,614,150
2010	153,034	1,642,857	67,773	2,293,050	7,899	7,157,144	1,146	165,204	136	143,291	225	40,723	3.7	21,322	543	1,696,400
2015	166,840	1,791,072	70,220	2,375,825	8,333	7,550,001	1,217	175,430	145	152,165	245	44,445	3.8	22,186	570	1,778,650
2020	180,647	1,939,286	72,666	2,458,600	8,767	7,942,858	1,288	185,676	153	161,039	266	48,167	4.0	23,050	596	1,860,900
2025	200,532	2,152,758	75,493	2,554,252	9,307	8,432,588	1,379	198,889	164	172,421	296	53,553	4.2	24,066	628	1,960,809

[1] Projections are based on "Preliminary Projections of Economic Activity in the Agricultural, Forestry and Related Economic Sectors of the U. S. and Its Water Resource Regions 1980, 2000, and 2020." ERS and Forest Service, USDA, August, 1967, P. iii, p.2.

[2] Sugar beets production is estimated on the basis of the projection of raw sugar production.

a_{km} represents the number of irrigable acres in water resource situation (k, m), and

A = 8,040,915 (the total number of irrigable acres in the study area).

The computed weights are given in Table VIII. Since the number of irrigable acres in the 48 water resource situations sum to A, the weights must sum to one. Hence we have:

$$\sum_{k=1}^{6} \sum_{m=1}^{8} W_{km} = 1.0$$

The production of any one crop is distributed among the 48 water resource situations by multiplying these weights by the appropriate *a priori* projected production for the period in question given in Table VII. For any period t let X_{nt}, n = 1, 2, ..., 8, represent the *a priori* projection of the study area's total production (in hundred weights, bushels, tons, or bales) for the eight irrigated crops in the model. The distribution of production among each water resource situation is given by:

$$X_{nkmt} = W_{km} \cdot X_{nt}$$

where X_{nkmt} is the upper limit for production of the n^{th} crop in water resource situation (k, m) in period t. These 48 upper limits for each crop are entered in the B_t vector of Model I as right hand side restrictions.

It is recalled that each of the 48 water resource situations have four types of soils. Given X_{nkmt}, its production among these four soils is allowed to be distributed on the basis of net returns. In each

TABLE VIII

WEIGHTS USED IN DISTRIBUTING PRODUCTION OF IRRIGATED CROPS AMONG THE FORTY-EIGHT WATER RESOURCE STRATA

Saturated Thickness Class in feet	Depth-to-Water Class in feet	0-50	51-100	101-150	151-200	201-250	251-300	301-400	> 400
	m k	1	2	3	4	5	6	7	8
0-100	1	.02613	.06596	.05131	.05022	.01538	.00991	.00475	.00369
101-200	2	.01881	.03908	.03315	.04876	.03723	.02629	.00781	.00131
201-300	3	.01179	.03970	.03758	.08098	.03480	.02049	.01557	.00329
301-400	4	.01224	.03261	.03706	.09286	.01384	.00434	.00480	.00139
401-500	5	.00055	.01222	.03168	.02161	.00206	.00209	.00228	.00087
> 500	6	.00341	.00869	.02369	.00706	.00015	.00011	.00040	.00000

water resource situation, the soils that give the highest net returns will be irrigated first. In this way marginal soils will not come into irrigated production unless the production goal for that water resource situation cannot be met, which is consistent with economic rationale. For those crops with dryland alternatives, whenever water costs on any water resource situation become so high that dryland production yields higher net returns, irrigated production ceases. However, since dryland crop yields are less than irrigated crop yields there may not be sufficient acres in that water resource situation to meet the production goal specified by the above procedure, and an infeasible solution may be encountered. To avoid such infeasibilities, dryland production in other water resource situations is allowed to pick up the slack. Since net returns on dryland activities are independent of water costs an intertransfer of quotas between water resource situations is made possible.

Quantity of Crops Produced: Model II

It was stated in Chapter II that Model II represents a situation in which the study area is allowed to produce more than its historic share of the projected U. S. production subject to the maximum rate of irrigation growth possible. The maximum number of irrigated acres at the various production periods were projected by an exponential growth model of the form developed by George A. Pavelis.[3] The model is given by

$$A_t = L - [(L - A_{15})\, e^{\beta(t-15)}], \quad t \geq 15 \qquad (1)$$

Where:

t = calendar year minus 1950,

A_t = acres irrigated in year (1950 + t),

L = 8,040,915, the maximum physical potential of irrigable acres in the indefinite future,

β = the continuous constant percentage decline in remaining potential as observed for the period 1958-1965, and

A_{15} = 1,554,898, the number of irrigated acres in 1965, the most recent year for which data were available.

Equation (1) indicates that acreage irrigated at time t is the difference between L, the maximum potential physical limit and that part of the limit not reached at time t. In other words $[(L - A_{15})\ e^{\beta(t-15)}]$ represents that portion of irrigable land that has not been irrigated (t-15) years after 1965. When t is equal to 15, (t-15) becomes zero and equation (1) reduces to A_{15}.

Estimation of β

First equation (1) was solved for β

$$A_t = L - [(L - A_{t-1})\ e^{\beta}],$$

$$e^{\beta} = \frac{L - A_t}{L - A_{t-1}}$$

$$\beta = \ln\left[\frac{L - A_t}{L - A_{t-1}}\right] \qquad (2)$$

then relation (2) was applied to the latter half of the observed data from 1950 to 1965 in order to give weight to the recent trend of growth in irrigated acres. Table IX shows the calculations for β. Using the average $\beta = -0.01900$ for the eight-year period 1958-1965, the number of acres irrigated in future years beyond 1965 was generated from relation (1). The results are shown in Table X.

TABLE IX

ESTIMATION OF β, 1959-1965

Year	t	A_t	$L - A_t$	$\frac{L - A_t}{L - A_{t-1}}$	$\beta_t = \ln \frac{L - A_t}{L - A_{t-1}}$
1958	8	632,392	7,408,523	--	--
1959	9	680,224	7,360,691	0.99354	-0.00648
1960	10	715,540	7,325,375	0.99520	-0.00481
1961	11	755,191	7,285,724	0.99459	-0.00543
1962	12	823,457	7,217,458	0.99063	-0.00941
1963	13	952,105	7,088,810	0.98218	-0.01799
1964	14	1,180,355	6,860,560	0.96780	-0.03273
1965	15	1,554,898	6,486,017	0.94541	-0.05614

The model assumes that the maximum physical potential will not be attained in the indefinite future. Growth will be asymptotic to the maximum limit. Since β is computed from observed growth in the past, like any predictive model it assumes past conditions that governed the increase in irrigated acres will prevail and there will be an adequate supply of water.

TABLE X

PROJECTIONS OF IRRIGATED ACRES BY THE EXPONENTIAL GROWTH MODEL

Year	Irrigated Acres	Periodic Change	Year	Irrigated Acres	Periodic Change
					227,329
1965	1,554,898		2020	5,759,522	
		587,735			206,731
1970	2,142,633		2025	5,966,253	
		534,477			187,995
1975	2,677,110		2030	6,154,248	
		486,045			170,962
1980	3,163,155		2035	6,325,210	
		442,002			155,471
1985	3,605,157		2040	6,480,681	
		401,949			141,381
1990	4,007,106		2045	6,622,062	
		365,527			128,571
1995	4,372,633		2050	6,750,633	
		332,404			116,920
2000	4,705,037		2055	6,867,553	
		302,283			106,324
2005	5,007,320		2060	6,973,877	
		274,891			96,690
2010	5,282,211		2065	7,070,567	
		249,982			87,929
2015	5,532,193		2070	7,158,496	

The first assumption is intuitively valid. If ground water in the future becomes economically and/or physically limiting, increments in irrigated acres may in fact be negative and, therefore, decline in the future. If such be the case, the model's projection will be upward biased after a certain time. The second assumption has a limitation in that future conditions will not be the same as they have been in the past. As irrigation continues to develop and the water table declines, prospective irrigators will have to consider the amount of water available for future use. They will be discouraged if they find volume is low and per unit cost of water is high. If the additional costs are not offset by higher product prices, again the projections will be upward biased. On the other hand, if a technological or an institutional breakthrough occurs that decreases the per unit cost and/or augments the water supply of the region, the converse could be true. However, these will not be serious limitations for the purpose the projected irrigated acres are used in the production model. Since the projection is set as an upper limit to the number of irrigated acres, the production model compares the profitability of irrigating the various crops at each soil and water stratum, and this upper limit will be met, if and only if, net returns on the last acre irrigated are higher than that of the corresponding dryland activity.

The Distribution of Production in the Study Area: Model II

The method used to distribute crop production among the 48 water resources of the study area in Model II is to apply the weights, W_{km}, of Table VIII to the total projected irrigated acreage.

For any period t let C_{nt}, n = 1, 2, ..., 6, represent the *a priori* projected upper limit of irrigated acres in the production of the n^{th} crop in the model. The production of each crop is distributed among each water resource situation according to:

$$c_{nkmt} = W_{km} \cdot C_{nt} \tag{3}$$

where c_{nkmt} is the upper limit to the number of irrigated acres in the production of the n^{th} crop in water resource situation (k, m) in period t. Two assumptions are made in the derivation of C_{nt} from the *a priori* projected irrigated acres of the exponential growth model. The first assumption involves the production of cotton and sugar beets. As one goes northbound from the southern tip of the study area the growing season gets shorter and shorter. This limits the production of cotton to only some of the counties in the Texas portion of the study area. Because of this geographic limitation, the declining importance of cotton in the textile industry, and the burgeoning surplus of the CCC, it is assumed that the expansion of cotton production will be at the levels projected for Model I. Likewise sugar beet production is held at the levels projected for Model I due to the limited capacity of growth for its market. The second assumption involves the distribution of the irrigated acreage of the crops used in the model given the declining water table condition of the aquifer as time progresses. For this purpose the results of Model I are analyzed and the average distribution of irrigated acres among the six irrigated crops (excluding sugar beets and cotton) up to and including 1990-1999, the period in which irrigation expansion reaches its peak, was taken as an index. The proportion of irrigated acreage among the six crops in Model I's solutions, Z_n, n = 1, 2, ..., 6, is given in Table XI. Let TC_t be the total number of irrigated acres projected for period t and let SC_t be the sum of irrigated acres devoted to the production of sugar beets and cotton for the corresponding period t in the solution of Model I. Then

C_{nt} is derived from the following formula:

$$C_{nt} = Z_n[TC_t - SC_t] \quad \text{and,}$$

$\left[\sum_{n=1}^{6} C_{nt} = TC_t - SC_t\right]$. C_{nt} is used in relation (3) above to calculate C_{nkmt}, which is entered in vector B_t of Model II as an upper limit to the number of irrigated acres in the production of the n^{th} crop in water resource situation (k, m) in period t.

TABLE XI

DISTRIBUTION OF IRRIGATED ACREAGE AMONG SELECTED CROPS ACCORDING TO THE SOLUTION OF MODEL I

Crop	Proportion (Z_n)
Wheat	0.5493
Grain Sorghum	0.3801
Corn Grain	0.0287
Silage	0.0281
Soybeans	0.0072
Alfalfa	0.0066

Capital and Labor

There are no restrictions in the two production models to limit the use of capital and labor. It is assumed that all the capital necessary can be borrowed at a seven percent simple interest rate and that the labor necessary for all operations can be hired at a wage rate of $1.50 per hour. However, there are two accounting restrictions to sum the total amount of capital and labor required for all production activities in the models.

Prices

The prices used in the crop enterprise budgets were the "adjusted normalized prices" issued by the Water Resource Council.[4] These are prices adjusted to minimize the direct price support effects or payments under government programs and are consistent with the supply and demand model used to project the national supply of agricultural commodities.[5]

Irrigation Systems and Water Costs

Two types of irrigation systems are used in the production models. A surface system is employed for those soils with a slope of less than three percent, i.e., soils classified as clay A and sand A. A self-propelled sprinkler system is used for soils with a steeper slope and management problems such as drainage and erosion, i.e., soils classified as clay B and sand B. The cost structures of these two irrigation systems were generated from the models developed by Shaffer and Eidman for the area around the Panhandle of Oklahoma.[6] The assumptions of these models and the costs of the different parts of the irrigation systems are given in Appendix F. The fixed, variable and total costs per acre inch were computed for both irrigation systems for well capacities ranging from 50-1,000 g.p.m. and well depths ranging from 79-925 feet. The estimated costs per acre inch are tabulated in Tables XLIV and XLV of Appendix F. The costs of pumping and applying water in each production period were obtained from these tables. The costs for each of the 48 water resource situations were selected based on the current saturated-thickness and depth-to-water conditions estimated by the model for that situation. As the availability of water during the summer months is crucial it is assumed that the decision to sink new wells is made on the basis of providing an adequate water supply for irrigating the summer crops. Hence this decision will be made only if the returns from the summer crops will be high enough to recover the investment costs over the life of the well. Total costs of water per acre inch are charged to all summer crop enterprises to reflect this assumption. Wheat enterprises are charged only the variable cost of water per acre inch.

The absolute amount of water available for irrigation has not been restricted in Model I and Model II as this is the variable to be observed as time progresses. At any production period the models make decisions of water application based upon current pumping and distribution costs and the profitability of alternative uses of water among the different crop enterprises. However, a water accounting restriction is included in both models to sum the volume of water used in each production period.

The Relationship Between Declining Water Table, Well Yield and Pumping Costs

A decline in the static water table is directly proportional to the net volume of water removed from the aquifer. Fader and his colleagues in studying the geohydrology of Grant and Stanton counties, southwest Kansas, computed an "aerial drawdown coefficient" for the purpose of estimating future water level declines.[7] The aerial drawdown coefficient is given by relation (4).

$$d = \frac{V}{AD} \tag{4}$$

Where:

d = the aerial drawdown coefficient,

V = the acre feet of water withdrawn from the aquifer,

A = the number of acres overlying the aquifer, and

D = the decline of the static water table in feet.

Using the volume of water withdrawn and changes in the water level for 1939-42 and subsequent years to 1963, they calculated the aerial drawdown coefficient to be 0.20. Assuming this coefficient is representative of the study area the decline in the static water table can be computed from relation (4) by rearranging the terms:

$$D = \frac{V}{Ad} \tag{5}$$

In using relation (5) for estimating water level changes in the future all quantities on the right hand side of the equation are known. A and d are constants. The net volume of water withdrawn from the aquifer, V, is computed by adjusting the total amount of water used for irrigation and municipal purposes for recharge.

It should be noted that such an approach yields an average decline in the water table throughout the study area. It assumes that water moves in relatively uniform manner from areas of high pressure to areas of low pressure throughout the aquifer. This may not be the case in reality as there will be pockets of heavy concentration of water pumpage and water may not move in sufficient velocity from areas of low pumpage to those of high pumpage to result in a uniform decline of the static water table in the short run. The use of an aerial drawdown coefficient equal to 0.20, which is greater than the coefficient of storage, equal to 0.15, in relation (5) is to reflect such an assumption. However, this may introduce a downward bias in the drawdown computed. If d = 0.15 instead of d = 0.20 were used in relation (5), the drawdowns calculated in each period would be greater. This means that the saturated-thickness would diminish at a faster rate and according to relation (6) well capacities will also decrease at a faster rate. The net effect would be a shorter economic life of the various water resource situations and a higher volume of water left in storage at the terminal period. Since d = 0.20 is an average figure obtained from one portion of the study area the figure that should be used may be somewhere between 0.15 and 0.20. In that case the use of d = 0.20 may bias drawdown downwards implying a longer economic life of some water resource situations despite their heavy concentration of pumpage and a lower volume of water in storage at their terminal period. A value of d = 0.20 was used in this study as the best available estimate.

The effect of a declining water table is two-fold. First it increases the pump lift (total dynamic head) by the amount it has declined, thereby increasing per unit pumping costs. The average pumping cost increase generated from the irrigation system model was $0.0192 per acre foot for each foot of decline in the water table. Second, a decline in the water table is tantamount to a decrease in the saturated-thickness of the water-bearing material, which affects well capacity. As the saturated-thickness decreases the new well capacity is computed from relation (6).[8]

$$Q_{t+1} = \frac{H^2_{t+1}}{H_t} Q_t \qquad (6)$$

Where:

Q_t = the original well capacity at period t,

Q_{t+1} = the subsequent well capacity at period t+1,

H_t = the original saturated-thickness at period t, and

H_{t+1} = the remaining saturated-thickness at period t+1.

Using the relations (5) and (6) the appropriate pump lift and well capacity is computed for the 48 water resource strata. These results are used to select revised costs per acre inch for the water buying activities in the linear programming models for the next production period.

This chapter has presented the input data used in the two RLP models and the procedures employed to revise their parameters from one production period to the next. Their results are presented and analyzed in the following chapter.

FOOTNOTES

[1] See pages 6 and 7 for matrix notation.

[2] Beck, et.al., p. 23, D. B. Sapik and R. L. Goematt, Availability of Ground Water in Cimarron County, Oklahoma, U. S. Geologic Survey, Unpub. Open File Atlas HA Sheet 1 (1969). Personal interview with Mr. Edwin Gutentag and Dr. Robert Prill of the U. S. Geologic Survey at Garden City, Kansas, September 13, 1967, and Buchanan, p. 10.

[3] George A. Pavelis, "Irrigation Policy and Long-Term Growth Functions", Agricultural Economics Research, Vol. XVII, No. 2 (April, 1965), p. 55.

[4] Water Resources Council, Interim Price Standards for Planning and Evaluating Water and Land Resources, Washington, D. C. (April, 1966).

[5] Ibid., p. 2.

[6] Ron E. Shaffer and Vernon R. Eidman, "The Cost Structure of Alternative Irrigation Distribution Systems", (Unpublished manuscript, Department of Agricultural Economics, Oklahoma State University).

[7] Fader, et.al., p. 49.

[8] This relation, developed for the Ogallala Formation in the Southern High Plains of Texas, was obtained by correspondence with Mr. Frank A. Rayner, Manager of the High Plains Underground Water Conservation District, Lubbock, Texas, and Mr. Frank Hughes, ERS, USDA. Texas A & M University, who reports that the "capacity of wells in the High Plains area decreases in remarkable agreement with the equation".

CHAPTER IV

RESULTS OF THE RECURSIVE LINEAR PROGRAMMING PRODUCTION MODELS

The changes projected for the study area by Models I and II are presented in this chapter. The depletion of the aquifer as projected by the two models and their effect on acres irrigated, quantities of crops produced under irrigation, the underground water storage levels, well capacities, the pattern of irrigated crop production among the 48 water resource situations and the aggregate annual income for the 1965 to 2070 period are presented and analyzed.

Results of Model I

Testing Model I

Elements of the input-output matrix and the right hand side vector were specified using Model I assumptions. The solution for 1965 conditions was obtained by using the Mathematical Programming System 360 (MPS 360) simplex algorithm on the IBM-360 computer. The key solution variables were compared with reported values of those variables in 1965 to test the validity of the production model. Criterion variables of the test were the quantities of the various irrigated crops, the total irrigated acreage and the total volume of water pumped during 1965. The model's solution showed that the study area's production was met exactly as specified and that the production process utilized 1,359,730 irrigated acres, 905,894 dryland acres and 2,347,744 acre feet of water. Since the production goals were set as right hand side equalities, the fact that they were met is not surprising. It merely asserts that the model is functional. Comparison of the model's irrigated acreage with that reported for 1965 shows a slight discrepancy. While Model I used 1,359,730 irrigated acres, the figure reported for 1965 in Table I is 1,528,789. The model solution included 169,059 or 12.43 percent fewer acres than the reported figure. Comparison of the water applied to irrigated acres reveals a striking closeness of the model's solution to that reported in 1965. The model's production used 2,347,744 acre feet whereas the reported amount of water applied to irrigated acres in 1965 is 2,323,759 acre feet. The difference is 23,985 acre feet or 1.03 percent of the reported figure. One may conclude that the model's solution on water use is accurate, but that the model's solution on the number of irrigated acres is slightly off target. However, a closer look and some practical observations suggest that the model's number of irrigated acres may not be off target after all.

In maximizing net returns Model I's solution selects the high rate of water application wherever a choice of high or low rate is available. In practice all irrigators may not apply the high rate as suggested by the model. Some may irrigate alternate rows, others may irrigate before planting only and some others may irrigate once or twice after planting. The method of reporting irrigated acreage does not reflect these differences. For instance, an acre of grain sorghum on which 16 inches of water have been applied and an acre of grain sorghum on which 24 acre inches have been applied are both reported as one irrigated acre. To the extent that this situation occurs in actual practice, farmers will have to irrigate more acres than the model indicates in order to meet the same production goal because yields per acre are smaller at low rates of water application than on higher rates. Another consideration that must not be overlooked is that farmers by design or accident overreport the number of acres they irrigate. One example of the latter is a situation where self propelled rotary sprinkler systems are used. A farmer irrigating a quarter section with such a system typically does not water approximately 30 acres on the four corners, but may report that the entire quarter section is irrigated. Furthermore, in Kansas where the state water resources board has shown some serious indication of its interest in controlling the rate of underground water withdrawal, farmers may tend to overreport their irrigated acres as a contingency for higher appropriations in the event of strict control. These considerations support and lend credence to the hypothesis that the model's solution of irrigated acres is a close approximation of the actual number of irrigated acres in 1965.

Projected Changes in Irrigated Acres and Underground Water in Storage

As noted previously the rapid growth of irrigation in the study area is a comparatively recent phenomenon and the aquifer had not been dewatered to any significant extent by 1965. Thus the growth of irrigation had not been limited because of increasing water costs as in the southern high plains of Texas.[1] The empirical results of Model I project that as the study area produces its national share of the eight irrigated crops in the future the number of acres irrigated annually increases from 1.36 million in the 1965-69 period to a peak of 1.63 million in the 1990-99 period. Then it declines to 1.46 million in the

2000-09 period. From then on it continues to decline until it reaches 0.85 million in the terminal period 2060-69. The decrease in irrigated acres is due to the decline in the water table as the water is mined from the aquifer. The projected irrigated acres and their period to period changes are given in columns (1) and (2), respectively, of Table XII.

The total quantity of water used annually follows the same periodic trend as the number of acres irrigated. It increases from 2.4 million acre feet in the 1965-69 period to its highest level, 3.03 million acre feet, in the 1990-99 period. The quantity gradually declines in subsequent periods to an annual usage of 1.84 million acre feet in the terminal period 2060-69. The projected annual withdrawal of water for irrigation, municipal and industrial purposes is given in columns (3) and (4), respectively, of Table XII. Column (5) shows the total annual withdrawal for all purposes and column (6) indicates the period to period change in this total. The estimated stock reserve of water in the aquifer at the beginning of each period is presented in column (7). The projection of the annual water use for municipal and industrial purposes steadily increases through time. The decline in the total annual water use after 2000 is caused by the decline in irrigated acres. As mining of the ground water continues through time, the stock reserve of water in the aquifer decreases steadily from an estimated 369.66 million to a projected 124.92 million acre feet by 2070. In relative terms about 66.21 percent of the 369.66 million acre feet will be removed from the aquifer by the terminal year 2070. Column (8) of Table XII shows the amount of water remaining in the aquifer at the beginning of each period as a percent of the 1965 level (369.66 million acre feet).

TABLE XII

CHANGES IN IRRIGATED ACRES AND GROUND WATER IN STORAGE AS PROJECTED BY MODEL I (1965-2070)

Period	No. Acres Irrigated Annually (1)	Period to Period Change in (1) (2)	Acre Feet Used Annually: For Irrigation (3)	Acre Feet Used Annually: For Municipal & Industrial (4)	Acre Feet Used Annually: For All Purposes (3) + (4) (5)	Period to Period Changes in (5) (6)	Total Ac. Ft. in Under Ground Storage at the Beginning of Period[1] (7)	Water in Storage as a Percent of 1965 (8)
1965-69	1,359,730	2,680	2,347,744	70,382	2,418,126	57,864	369,663,804	100.00
1970-79	1,362,410	190,536	2,346,337	129,653	2,475,990	296,446	358,949,554	97.10
1980-89	1,552,946	72,426	2,623,269	149,167	2,772,436	258,280	336,890,434	91.14
1990-99	1,625,372	-169,411	2,865,379	162,436	3,030,716	-55,749	311,866,854	84.36
2000-09	1,455,961	-18,566	2,797,019	177,948	2,974,967	-116,489	284,260,474	76.90
2010-19	1,437,395	-210,712	2,663,333	195,145	2,858,478	-274,414	257,211,584	69.58
2020-29	1,226,683	-4,044	2,366,059	212,245	2,584,064	-5,760	231,327,584	62.58
2030-39	1,222,639	-19,000	2,354,719	229,345	2,578,304	-6,858	208,187,724	56.32
2040-49	1,203,639	-85,715	2,325,001	246,445	2,571,446	-153,056	185,105,464	50.07
2050-59	1,117,924	-264,492	2,154,845	263,545	2,418,390	-582,537	162,091,784	43.85
2060-69	853,432		1,555,208	280,645	1,835,853		140,608,664	38.04
2070							124,950,914	33.80

[1] For any period after 1965-69 column (7) is obtained by subtracting n[column (5) = 270,078] from column (7)'s entry in the previous period. n is the number of years in the previous period and 270,078 is the mean annual recharge in acre feet.

The rate of decline in the water table is directly proportional to the amount of net water withdrawal per year as calculated by relation (5) of Chapter III. It increases steadily from 1.3 feet per year in the 1965-69 period to a peak of 1.72 feet per year in the 1990-99 period. The decrease in the rate of net water withdrawal results in smaller water table declines during subsequent periods. In the terminal period 2060-69 it is projected to be 0.97 feet per year and by 2070 the cumulative water table decline over the 105 year period (1965-2070) is 153 feet.

The effect of the decline in the water table is two fold. First, as the saturated-thickness of the aquifer decreases the well capacity declines according to relation (6) of Chapter III. Thus wells have to pump more hours in order to deliver the same volume of water as before. Secondly, the depth-to-water increases by the same amount as the decline in the water table which means each unit of water will have to be pumped more distance. The combined effect of both is to increase the per unit pumping cost of water. The projected annual decline in the water table and the periodic decline in the well capacity for each of the six initial saturated-thickness classes is given in Table XIII. The results of Model I indicate that the well capacity of the smallest saturated-thickness class (0-100 feet) declines rapidly from an initial capacity of 500 g.p.m. to 34 g.p.m. by 1990, which is considered to be too low to sustain irrigation systems. Consequently, irrigation ceases on all soils of this saturated-thickness class by 1990. The area involved is some 1.8 million acres and accounts for about 22.74 percent of the total irrigable land in the study area. In the second saturated-thickness class (101-200 feet) well capacity declines from 1,000 g.p.m.

in 1965 to 20 g.p.m. in 2050, which is considered too low to sustain irrigation systems. Irrigated production of crops ceases on soils of this saturated-thickness class after the production period 2040-49. The area involved totals to 1,708,092 acres which is about 21.24 of the total irrigable land. The rate of decline in well capacity is much slower on the other saturated-thickness classes. The results of Model I indicate that wells in these saturated-thickness classes have a long physical life extending beyond the assumed planning horizon of 100 years. At the terminal year 2070 wells in saturated-thickness class 201-300 feet will yield 150 g.p.m., wells in saturated class of 301-400 feet will yield 320 g.p.m., and wells in saturated-thickness class of more than 500 feet will yield approximately 520 g.p.m.

At this point a word of caution in the interpretation of the results is in order. As the model is run once for a discrete 10-year period, computations of the decline in the water table, well capacities and, hence, water costs for any period t are made on the basis of the results of period t - 1. Therefore, the values of these variables reflect the water situation at the beginning of period t. This implies that (1) water costs toward the end of period t are biased downwards and, hence, the model encourages more water use and tends to bias net returns to irrigation upwards and (2) in the process of declining well capacities, some of the water resource situations may reach well capacities around 50 g.p.m. (which is considered to be too low to maintain irrigation systems) towards the middle of period t instead of the end of period t which again tends to make the model encourage more water use and, hence, bias the net returns to irrigation upwards. The alternative to eliminate this bias would have been to obtain solutions on an annual basis which would be too cumbersome and costly.

The above discussion summarizes the projected physical changes that will occur if events in the future conform to, or approximate those assumed in Model I. The following discussion considers the economic effects of the projected changes in the aquifer on the pattern of crop production for the periods between 1965 and 2070. First the annual distribution of irrigated and dryland acreages of the crops and their associated production, gross and net returns is discussed for the study area as a whole. Then the production pattern among the 48 water resource situations as water costs change from one production period to the next is presented.

Projected Annual Irrigated and Dryland Crop Acreages, 1965-2070

It is recalled that the basic assumption in Model I is that the study area will produce its share of the projected national supply of the eight irrigated crops from 1965 through 1929 and that it will attempt to maintain the same levels of production as in the 2020-29 period, resources permitting from 2030 to 2070. In general, as the model fulfills these production goals irrigated acreages of each crop increase to a peak in the early periods and then decline to a low in the terminal period, whereas the dryland acreages on grain sorghum, wheat, alfalfa and cotton increase as time progresses. This general trend results from the combined effect of an increased production goal the model must meet from one production period to another and the declining water table. On one hand the increased production goals tend to increase irrigated acreage of each crop. On the other hand, the rising water costs on some of the water resource situations tend to decrease irrigated acreage by diverting production to dryland for those crops that have dryland alternatives and by terminating production altogether for those crops produced only on irrigation when their net returns per acre fall to zero or less. In the early production periods the former tendency prevails as water is comparatively cheap. In the latter periods water pumping costs increase resulting in a decrease in irrigated acreage and an increase in dryland acreage. While this is the general trend there are a few fluctuations of irrigated acreage on some crops, especially wheat, caused by adjustments to changes in water costs and increased production goals. As the well capacity on some water resource situations falls from above 750 g.p.m. to some level below 750 g.p.m. the pipes and engines designed initially for 1,000 g.p.m. are changed and total water costs of sprinkler systems may drop as much as $2.52 per acre foot and as much as $1.32 per acre foot due to the installation of smaller pipes and smaller engines. As well capacity declines further water costs start to rise again until a transition to less than 350 g.p.m. is made at which time smaller pipes and smaller engines are installed and total water costs may drop as much as $2.53 per acre foot and variable costs may decrease as much as $1.87 per acre foot. As well capacity declines further water costs being to rise again. Such changes in well capacities do not occur simultaneously on all water resource situations. The asterisks on the well capacities of Table XIII indicate when such fluctuations in sprinkler water costs take place. The model responds to these cost changes by increasing or decreasing irrigated acres on some of the crops.

The projected annual irrigated and dryland acreages of all crops for the entire study area are presented in Table XIV. The annual

TABLE XIII

DECLINE OF THE WATER TABLE AND THE RESULTING WELL CAPACITIES OF THE SIX SATURATED THICKNESS CLASSES AS PROJECTED BY MODEL I (1965-2070)

	Water Table Decline in Feet		Well Capacities in GPM[a] Saturated Thickness Class[b]					
Period	Annual	Cumulative	<100'	101-200'	201-300'	301-400'	401-500'	>500'
1965-69	1.30	--	500	1,000	1,000	1,000	1,000	1,000
1970-79	1.41	6.48	365	905	952	966	974	978
1980-89	1.59	20.58	171*	779	847	891	913	925
1990-99	1.72	36.46	34	599*	734*	807	847	870
2000-09	1.69	53.66		431	620	721*	778	813
2010-19	1.60	70.56		299*	523	645	716*	761
2020-29	1.44	86.56		186	429	569	654	708*
2030-39	1.44	100.96		111	350*	509	603	665
2040-49	1.43	115.36		57	292	452	554	623
2050-59	1.33	129.66		20	233	399	508	583
2060-69	0.97	142.96			184	350*	466	546
2070	--	152.66			152	320	437	520

[a] Indicate values at the beginning of period.

[b] Initial 1965 conditions.

*Indicate well capacities at which water costs for sprinkler systems decrease.

TABLE XIV

MODEL I's PROJECTIONS OF ANNUAL IRRIGATED AND DRYLAND ACREAGES OF THE VARIOUS CROPS (1965-2070)

	Grain Sorghum		Wheat		Corn Grain	Silage	Alfalfa		Sugar Beets	Cotton		Soybeans	Total Acres	
Period	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Irrigated	Irrigated	Dryland	Irrigated	Irrigated	Dryland	Irrigated	Irrigated	Dryland
1965-69	520,103	434,006	743,636	470,036	36,236	35,506	9,074	1,358	5,577	1,223	494	8,379	1,359,730	905,894
1970-79	505,267	1,001,787	750,592	1,130,211	40,543	37,547	8,811	10,717	6,608	1,213	1,726	10,495	1,361,076	1,503,753
1980-89	592,527	1,275,703	837,553	1,320,899	45,583	45,542	10,204	12,794	7,638	1,439	2,046	11,803	1,552,286	2,611,441
1990-99	721,490	1,529,263	769,491	1,808,385	51,245	47,901	11,611	14,634	8,669	1,552	2,208	13,410	1,625,372	3,354,488
2000-09	890,599	1,542,242	426,256	3,193,494	44,372	42,047	13,180	14,683	7,890	1,640	2,379	11,413	1,437,395	4,752,797
2010-19	1,086,476	1,555,875	234,324	4,117,271	49,526	47,521	14,508	18,577	9,477	1,429	3,403	12,576	1,455,836	5,695,125
2020-29	957,828	2,309,870	129,533	4,469,219	49,526	55,911	11,958	29,531	9,477	1,056	4,410	11,396	1,226,683	6,813,029
2030-39	939,823	2,447,445	179,493	4,296,053	37,116	35,809	10,839	39,444	9,477	959	4,672	9,121	1,222,639	6,783,112
2040-49	938,376	2,454,062	166,614	4,338,064	35,910	32,700	10,776	34,944	9,477	813	5,879	8,973	1,203,639	6,832,136
2050-59	869,132	2,418,375	160,225	4,384,207	35,910	28,186	7,842	34,940	6,876	782	5,150	8,973	1,117,926	6,842,672
2060-69	536,763	2,657,427	238,646	4,172,186	31,949	27,788	6,001	34,940	6,871	782	5,150	4,632	853,432	6,869,701

irrigated acreage of grain sorghum more than doubles by 2010. It increases from 520,103 acres in the 1965-69 period to about 1.09 million acres in the 2010-19 period, which is an increase of 109 percent. During the same span of time the dryland grain sorghum acreage changed from an annual 434,006 acres to 1.56 million acres, an increase of 258 percent. In subsequent periods, the annual irrigated acreage of grain sorghum gradually declines to a terminal low of 536,763 acres, which is about three percent more than the initial level. The slack in the production is met by the substantial increase of the dryland grain sorghum acreage. While the annual irrigated acreage of grain sorghum decreases by 128,648 acres (from 1.08 million in the 2010-19 period to 0.958 million acres in the 2020-29 period), the annual dryland acreage of grain sorghum increases by 753,955 acres. In the terminal period, 2060-69 the annual dryland acreage of grain sorghum rises to 2.66 million acres which is about six times the initial period.

Net return per acre of irrigated wheat is low compared to the other irrigated crops. Thus the annual irrigated acreage for wheat increases at a very slow rate from 743,436 acres in the 1965-69 period and reaches a peak of 837,553 acres in the 1980-89 period. This is an increase of only 13 percent over the initial level. In the same period the dryland acreage of wheat increased from 470,036 to 1.32 million acres, which is a growth of 181 percent over the initial period. From 1990 to 2030 the annual irrigated acreage of wheat steadily declines to a low of 129,538 acres and then fluctuates in the remaining four periods due to decreased sprinkler system costs in saturated-thickness classes (201-300 feet and 301-400 feet).

The annual irrigated acreage of corn in the study area increases from 36,236 in the 1965-69 period to a peak of 51,245 in the 1990-99 period, an increase of 14.14 percent and then declines to 31,949 acres in the terminal period 2060-69.

The annual irrigated acreage of silage increases from 35,506 in the 1965-69 period to 47,901 in the 1990-99 period. It declines in the next two periods and then increases to a peak of 55,911 acres in the 2020-29 period, a growth of about 57 percent over the initial level. From then on it declines to a low of 27,788 acres in the terminal period. This fluctuation is due to the response of silage production to decreases in water costs of sprinkler systems in the two saturated-thickness classes (101-200 feet and 401-500 feet) in the 2010-19 period.

The annual irrigated acreage of alfalfa and sugar beets increases to a peak in the 2010-19 period and then declines to a low in the terminal period. For cotton the peak occurs one period sooner, in the 2000-09 period. Soybeans reaches its peak of 13,400 acres in the 1990-99 period. It decreases to 11,413 in the following period and increases to 12,576. From then on it gradually decreases to 4,632 acres in the 2060-69 period.

Projected Annual Production of Crops and Their Aggregate Annual Gross and Net Returns

The projected annual irrigated and dryland crop production and the associated aggregate gross and net returns are presented in Table XV. Since the analysis assumes yields per acre are held constant over time the trend of irrigated and dryland production of each crop follows exactly the same trend as that of the projected annual irrigated and

TABLE XV

MODEL I's PROJECTION OF ANNUAL PRODUCTION OF CROPS AND THEIR AGGREGATE GROSS AND NET RETURNS (1965-2070)

Period	Grain Sorghum		Wheat		Corn Grain	Silage	Alfalfa		Sugar Beets	Cotton		Soybeans	Annual Gross Returns From		Annual Net Returns From		Total Annual Net Returns	Estimated Primary Irrigation Benefits
	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Irrigated	Irrigated	Dryland	Irrigated	Irrigated	Dryland	Irrigated	Irrigated	Dryland	Irrigated	Dryland		
	1,000 Cwt		1,000 Bu.		1,000 Bu.	1,000 Tons	1,000 Tons		1,000 Tons	1,000 Bales		1,000 Bu.	1,000 Dollars		1,000 Dollars		1,000 Dollars	1,000 Dollars
1965-69	32,098	5,946	34,417	6,486	4,711	698	68	2.4	112	1.6	0.2	293	116,066	19,179	40,639	9,743	47,382	18,418
1970-79	31,263	13,724	34,954	15,597	5,271	734	66	18.8	132	1.7	0.8	367	116,651	45,475	40,662	15,587	56,248	18,443
1980-89	36,709	17,477	39,024	18,228	5,926	828	77	22.4	153	2.0	1.0	413	133,437	55,530	45,622	19,049	64,672	20,316
1990-99	44,687	20,951	36,048	24,956	6,662	946	87	25.6	173	2.2	1.1	469	144,325	70,990	48,197	24,333	72,530	21,869
2000-09	55,004	21,129	20,274	44,070	5,768	831	99	25.7	158	2.3	1.2	399	136,531	99,015	42,263	33,722	75,985	19,275
2010-19	66,956	21,316	11,306	56,818	6,438	940	109	28.8	190	2.0	1.7	440	145,208	117,402	40,206	40,058	80,264	17,484
2020-29	59,377	28,895	6,449	61,675	6,438	940	92	45.8	190	1.5	2.2	440	125,199	137,277	31,045	44,688	75,933	12,281
2030-39	58,261	30,011	8,839	59,286	4,825	682	81	54.2	190	1.3	2.4	319	123,096	135,882	28,056	43,587	71,643	8,734
2040-49	58,172	30,100	8,259	59,865	4,668	634	81	54.2	190	1.1	2.6	314	121,628	136,868	24,469	43,932	68,401	5,415
2050-59	53,879	30,107	7,622	60,502	4,668	551	59	54.2	138	1.1	2.6	314	112,028	137,793	18,330	44,638	62,968	709
2060-69	33,272	32,507	10,548	57,576	4,153	455	45	54.2	137	1.1	2.6	162	80,571	137,555	14,261	43,916	58,177	48

dryland acreage of each crop. The annual aggregate gross return from irrigated production of crops increases from $116.1 million in the 1965-69 period to a peak of $145.2 million in the 2010-19 period, an increase of about 25 percent. Gross income from irrigation declines to a terminal low of $80.57 million in the 2060-69 period, which is about 69 percent of the initial level. Despite the continued growth of annual aggregate gross returns from irrigated production in the 1965 to 2020 periods, annual aggregate net returns from irrigation reaches its highest level of $48.20 million in the 1990-99 period, an increase of about 19 percent over the initial level, and then declines steadily to its lowest level of $14.26 million in the terminal period, 1960-69, which is about 35 percent of the initial level. While annual aggregate gross returns from irrigation increases by $8.68 million between 2000 and 2010, annual aggregate net returns from irrigation decreased by $2.06 million over the same period. This reflects a net annual loss of more than $10.74 million due to rising water costs in a ten-year period.

Annual aggregate gross returns from dryland crop production increase from $19.18 million in the initial period to $137.28 million in the 2020-29 period. In the remaining four periods, it fluctuates mainly due to the fluctuation in dryland wheat production. The highest level of annual aggregate gross return for dryland production is $137.79 million in the 2050-59 period. Annual aggregate net return from dryland production of crops follows the same trend as the annual aggregate dryland gross return. It increases from $9.74 million in the initial period to a peak of $44.69 million in the 2020-69 period. Then as the dryland wheat production fluctuates it swings up and down in the last four periods. As annual aggregate net return from irrigation declines after 1990 annual aggregate net returns from dryland production continue to grow for the next three periods. This total annual aggregate net return increases from \$47.32 million in the initial period to a peak of \$80.26 million in the 2010-19 period, an increase of 69 percent, and then declines to \$58.18 million in the terminal period 2060-69. This is about 123 percent of the initial level. It is important to note that this total annual aggregate net return is maintained at a high level by an increase of more than 700 percent in dryland acres over the 1965-69 period. The source of this increase is that part of the 8.0 million acres of cropland that was being used for the production of other crops like barley, oats, hay, etc.

The annual primary irrigation benefits, which are defined here as the net income added to the aggregate net farm income of the study area by irrigation, were estimated based on the Model I solutions according to the following relation:

$$\overline{PB}_t = \overline{NR}_t - [(\sum_{j=1}^{4} \sum_{i=1}^{4} N_i C_{it} + N_j S_{jt}) + 1.25 I_t] \qquad (1)$$

Where:

$\overline{PB}_t$ is the annual primary irrigation benefit in period t,

$\overline{NR}_t$ is the annual net return from irrigation in period t,

$i = j = 1, 2, 3, 4$ is grain sorghum, wheat, alfalfa, and cotton, respectively,

N_i is the dryland net return per acre of the i^{th} crop on clay loam soils,

N_j is the dryland net return per acre of the j^{th} crop on sandy loam soils,

C_{it} is the amount of clay loam acres on which the i^{th} crop would be produced without irrigation in period t,

S_{jt} is the amount of sandy loam soils on which the j^{th} crop would be produced without irrigation in period t,

I_t is the total number of acres on which corn grain, corn silage, sugar beets and soybeans are produced in period t, and

1.25 is the dryland opportunity cost of I_t.

The estimates shown in the last column of Table XV indicate that the annual primary irrigation benefits increase from $18.42 million in the 1965-69 period to a peak of $21.87 million in the 1990-99 period, when irrigation development reaches its zenith. Annual primary irrigation benefits steadily decline in subsequent periods to a low of $48,000 in 2060.

Changes in the Production Pattern Among Water Resource Situations

In response to changes in production goals and changes in the costs of irrigation water from one production period to the next, the model increases or decreases the irrigated acreage of each of the eight crops on each of the 48 water resource situations. The results of Model I show that, in general, the smaller the saturated-thickness and the greater the depth-to-water the more sensitive the resource is to changes in water costs. In order to facilitate the presentation of the changing pattern of production among the water resources as time proceeds, a reference system shall be introduced at this point. The 48 water resource situations shall be designated as:

WRS k-m

Where:

WRS = water resource situation,

k = 1, 2, ..., 6 refers to the k^{th} saturated-thickness class, and

m = 1, 2, ..., 8 refers to the m^{th} depth-to-water class.

Each number in k and m is as previously defined in Chapter III. Thus WRS 1-1 refers to the resource in the first saturated-thickness class (0-100 feet) and the first depth-to-water (0-50 feet), and WRS 6-8 refers to the resource with the greatest saturated-thickness class (>500 feet) and the greatest depth-to-water (>350 feet).

The rows and columns in Table XVI are designated using this reference scheme to represent the 48 water resource situations, WRS 1-1 through 6-8. The letters in the cells represent the crops grown under irrigation in each water resource situation for the 11 production periods 1965-69 through 2060-69. Blanks indicate that no irrigated production takes place. Table XVI shows the general pattern of irrigated crop production among each WRS in all production periods under the assumptions of Model I. In particular it shows the life of the aquifer in each WRS for each of the eight irrigated crops. One can determine when the model indicated it would no longer be economical to irrigate a crop on a WRS by following the letter representing the crop down the appropriate column. For instance, in WRS 2-1 following S down the column one notes that the production of irrigated grain sorghum ceases on WRS 2-1 at the end of the 2010-19 period. One can also determine the depth-to-water situations producing a given crop during a production period by following the letter across the appropriate row. By tracing S in WRS 2- across the rows one notes that grain sorghum is not irrigated on WRS 2-7 and WRS 2-8 even in the initial period. Note that for

TABLE XVI

THE PATTERN OF IRRIGATED CROP PRODUCTION AMONG THE FORTY-EIGHT WATER RESOURCE SITUATIONS AS PROJECTED BY MODEL I (1965-2070)

Saturated Thickness	Depth to Water	0-50'	51-100'	101-150'	151-200'	201-250'	251-300'	301-350'	>350'
	Period	WRS 1-1	WRS 1-2	WRS 1-3	WRS 1-4	WRS 1-5	WRS 1-6	WRS 1-7	WRS 1-8
WRS 1 0-100'	1965-69	s w c l* a b t y	s w c l a b t y	w c l a b t y	c l a b t y	c l b y	c l b y	c l b y	c l b y
	1970-79	c l a b y	c l b y	c l b y	c l b y	c l b y	c b y	c b y	c b
	1980-89	c l b y	c l b y	c l b y	c l b y	c l b	c l b	c l b	c b
	1990-99								
	2000-09								
	2010-19								
	2020-29								
	2030-39								
	2040-49								
	2050-59								
	2060-69								

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*See key on page 96.

TABLE XVI (Continued)

Saturated Thickness	Depth to Water	0-50'	51-100'	101-150'	151-200'	201-250'	251-300'	301-350'	>350'
	Period	WRS 2-1	WRS 2-2	WRS 2-3	WRS 2-4	WRS 2-5	WRS 2-6	WRS 2-7	WRS 2-8
WRS 2- 101-200'	1965-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	c l a b t y	c l a b y
	1970-79	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	c l a b y	c l a b y	c l a b y
	1980-89	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	w c l a b t y	c l a b y	c l a b y	c l a b y
	1990-99	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	w c l a b t y	c l a b y	c l a b y	c l a b y
	2000-09	s c l a b t y	s c l a b t y	s c l a b t y	s c l a b t y	c l a b y	c l a b y	c l a b y	c l b y
	2010-19	s c l a b t y	s c l a b y	s c l a b y	s c l a b y	c l a b y	c l a b y	c l b y	c l b y
	2020-29	c l a b y	s c l a b y	c l b y	c l b y	c l b	c l b	c l b	c l b
	2030-39	c b	b	b	b	b	b	b	b
	2040-49	b	b	b	b	b	b	b	b
	2050-59								
	2060-69								

TABLE XVI (Continued)

Saturated Thickness	Depth to Water Period	0-50' WRS 3-1	51-100' WRS 3-2	101-150' WRS 3-3	151-200' WRS 3-4	201-250' WRS 3-5	251-300' WRS 3-6	301-350' WRS 3-7	>350' WRS 3-8
WRS 3- 201-300'	1965-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	c l a b t y	c l a b y
	1970-79	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	w c l a b y	c l a b y	c l a b y
	1980-89	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	c l a b y	c l a b y	c l a b y
	1990-99	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b t y	c l a b y	c l a b y	c l a b y
	2000-09	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b t y	s c l a b y	c l a b y	c l a b y
	2010-19	s w c l a b t y	s c l a b t y	s c l a b t y	s c l a b t y	s c l a b t y	s c l a b y	s c l a b y	c l a b y
	2020-29	s c l a b t y	s c l a b t y	s c l a b t y	s c l a b y	s c l a b y	s c l a b y	s c l a b y	s c l a b y
	2030-39	s c l a b t y	s c l a b t y	s c l a b y	s c l a b y	s c l a b y	s c l a b y	s c l a b y	s c l a b y
	2040-49	s c l a b t y	s c l a b y	s c l a b y	s c l a b y	s c l a b y	s c l a b y	s c l a b y	s c l b y
	2050-59	s c l a b y	s c l a b y	s c l a b y	s c l b y	s c l b y	c b y	c b y	c b y
	2060-69	s c l a b y	l b	c l b	c l b	c b	c b	b	b

TABLE XVI (Continued)

Saturated Thickness	Depth to Water	0-50'	51-100'	101-150'	151-200'	201-250'	251-300'	301-350'	>350'
	Period	WRS 4-1	WRS 4-2	WRS 4-3	WRS 4-4	WRS 4-5	WRS 4-6	WRS 4-7	WRS 4-8
WRS 4- 301-400'	1965-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	w c l a b y	c l a b y
	1970-79	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	c l a b y	c l a b y
	1980-89	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	c l a b y	c l a b y	c l a b y
	1990-99	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	c l a b t y	c l a b y	c l a b y
	2000-09	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b t y	s c l a b y	c l a b y
	2010-19	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b t y	s c l a b y	s c l a b y	s c l a b y
	2020-29	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b t y	s c l a b t y	s c l a b y	s c l a b y	s c l a b y
	2030-39	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b t y	s c l a b t y	s c l a b y	s c l a b y	s c l a b y
	2040-49	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b t y	s c l a b y	s c l a b	s c l a b	s c l a b y
	2050-59	s w c l a b t y	s w c l a b t y	s cl a b t y	s c l a b t y	s c l a b y	s c l a b	s c a b	s c a b y
	2060-69	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b t y	s c l a b y	c a b	s c a b	s c a b y

TABLE XVI (Continued)

Saturated Thickness	Depth to Water	0-50'	51-100'	101-150'	151-200'	201-250'	251-300'	301-350'	>350'
	Period	WRS 5-1	WRS 5-2	WRS 5-3	WRS 5-4	WRS 5-5	WRS 5-6	WRS 5-7	WRS 5-8
WRS 5- 401-500'	1965-69	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	c l a b y	c l a b y
	1970-79	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	w c l a b y	c l a b y	c l a b y
	1980-89	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	c l a b y	c l a b y	c l a b y
	1990-99	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	c l a b y	c l a b y	c l a b y
	2000-09	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b y	s c l a b t y	s c l a b y	c l a b y
	2010-19	s w c l a b y	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b y	s c l a b t y	s c l a b y	s c l a b y
	2020-29	s w c l a b y	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b y	s c l a b t y	s c l a b y	s c l a b y
	2030-39	s w c l a b y	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b y	s c l a b t y	s c l a b y	s c l a b y
	2040-49	s w c l a b y	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b y	s c l a b t y	s c l a b y	s c l a b y
	2050-59	s w c l a b y	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b y	s c l a b t y	s c l a b y	s c l a b y
	2060-69	s w c a b y	s w c a b t y	s w c a b t y	s c l a b t	s c l a b	c l a b t	s c l a b	s c l a b

TABLE XVI (Continued)

Saturated Thickness	Depth to Water	0-50'	51-100'	101-150'	151-200'	201-250'	251-300'	301-350'	>350'
	Period	WRS 6-1	WRS 6-2	WRS 6-3	WRS 6-4	WRS 6-5	WRS 6-6	WRS 6-7	WRS 6-8
WRS 6- >500'	1965-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b y	w c l a b	c l a b y	
	1970-79	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b	w c l a b	c l a b y	
	1980-89	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	c l a b	c l a b	c l a b y	
	1990-99	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b	c l a b	c l a b y	
	2000-09	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b	s c l a b	s c l a b y	
	2010-19	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b	s c l a b	s c l a b y	
	2020-29	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b t y	s c l a b	s c l a b	s c l a b y	
	2030-39	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b	s c l a b	s c l a b y	
	2040-49	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c l a b	s c l a b	s c l a b y	
	2050-59	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c a b	s c l a b	s c l a b y	
	2060-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s c a b	s c l a b	s c l a b	

Key: s = Grain Sorghum, c = Corn, a = Alfalfa, t = Cotton,
w = Wheat, l = Silage, b = Sugarbeets, y = Soybeans

most crops the economic life of the water resource situations is longer in those with initial saturated-thickness classes of 200 feet or more, and depth-to-water of less than 200 feet.

As time progresses toward 2020 the production goals of Model I increase as well as water costs. Much of the adjustment to this increased production goal and rising water costs is borne by the crops that have dryland alternatives. This occurs for two reasons. First, sorghum and wheat have lower net returns per irrigated acre than any other irrigated crop and as water costs rise net returns per acre on some water resources dwindle to a level equal to or less than their dryland net returns, and are shifted to dryland production when it becomes more profitable. Secondly, as Model I strives to maximize net returns subject to meeting the production goals it continues to produce the crops that are grown only with irrigation (corn, silage, soybeans and sugar beets) as long as their net returns are positive. Therefore, in water situations where irrigable acres become limiting in fulfilling the production goal of corn, silage, soybeans and sugar beets, the other crops are shifted to dryland production elsewhere even though they have higher net returns per acre irrigated than in their dryland alternatives. When such situations arise, wheat is the most sensitive crop to be shifted to dryland first, followed by cotton, grain sorghum and alfalfa in that order. Among the crops that are produced only under irrigation, soybeans have the lowest net returns per irrigated acre and are the first to be forced out of production as water costs increase. They are followed by silage, corn grain and then sugar beets in that order. Again by following the letters, down column-wise and across row-wise in Table XVI, one can perceive the pattern of irrigated production changing as described above.

Results of Model II

Testing the Model

The assumption of Model I, that the study area will produce a maximum of its historic share of the projected national supply of the eight irrigated crops is relaxed in Model II. In this model irrigation was permitted to increase to the full irrigated acreage projected by the exponential growth model developed in Chapter III. In addition, the study area's historic share of the projected national supply of the eight irrigated crops was posited as a minimum production goal up to 2030. The minimum and the maximum on sugar beet and cotton production were the same. All other crops had no maximum production goals. After 2030 the minimum production assumption was conditioned by the availability of resources to yield positive net returns in irrigation, i.e., for the crops that have no dryland alternatives (corn, silage, soybeans and sugar beets) the minimum production goal will be met only if net returns are positive.

Elements of the input-output matrix and the right hand side vector were specified according to the assumptions above for conditions prevailing in 1965. The Model II computer solutions were obtained and the key variables compared to those reported in 1965 to test whether the model was operational. The test variables were the total number of irrigated acres, the total volume of water used and the quantities of the various irrigated crops. Model II's solution showed that the irrigated acres of all crops totaled 1,554,898 acres, exactly the number reported in 1965. Sugar beets and cotton were produced in exactly the quantities specified for 1965. The quantities of the remaining six crops produced were well above the minimum set as the production goal for 1965. The quantity of water pumped by Model II was 2.7 million acre feet versus 2.3 million reported in 1965. This is an excess of 0.4 million acre feet or about 17 percent more than that reported. In view of these comparisons, one can conclude that the model is operational in as far as it met the basic assumptions it incorporated. The Model II solutions show that, except for sugar beets and cotton, the study area produced more than its historic share of the national supply of irrigated crops. The fact that more water is used than reported in 1965 is concomitant to this excess production. It was shown by the results of Model I that when production goals were met exactly as reported for 1965 the amount of water pumped was within one percent of that reported in 1965. In general the results of Model II indicated that if irrigation develops in the study area at the rates projected, the use of resources and the ensuing production of crops will be more intensive and that ground water will be mined at a faster rate than was indicated by Model I. The results of Model II are presented in the following section and a comparison of the key variables in the results of Model I and Model II follows.

Projected Changes in Irrigated Acres and Underground Water in Storage

The projected number of annual irrigated acres, the rate of ground water withdrawal and the amount of ground water in storage at the beginning of each period are presented in Table XVII. The results of Model II indicate that the number of annual irrigated acres increases

TABLE XVII

CHANGES IN IRRIGATED ACRES AND GROUND WATER IN STORAGE AS PROJECTED BY MODEL II (1965-2070)

			Acre Feet Used Annually					
Period	No. Acres Irrigated Annually (1)	Period to Period Change in (1) (2)	For Irrigation (3)	For Municipal & Industrial Purposes (4)	For All Purposes (3) + (4) (5)	Period to Period Change in (5) (6)	Total Ac. Ft. in Under Ground Storage at the Beginning of Period[a] (7)	Water in Storage as a Percent of 1965 (8)
1965-69	1,554,898		2,685,296	70,382	2,755,678		369,663,804	100.00
		1,116,067				1,984,185		
1970-79	2,670,965		4,610,210	129,653	4,739,863		357,235,804	96.64
		107,983				207,765		
1980-89	2,778,948		4,798,461	149,167	4,947,628		312,537,954	84.55
		584,973				1,021,826		
1990-99	3,363,921		5,807,018	162,436	5,969,454		265,762,454	71.89
		-573,460				-978,537		
2000-09	2,790,461		4,812,969	177,948	4,990,917		208,768,694	56.48
		-234,018				-455,165		
2010-19	2,556,443		4,340,607	195,145	4,535,752		161,560,304	43.70
		-709,065				-1,271,639		
2020-29	1,847,378		3,051,868	212,245	3,264,113		118,903,564	32.16
		-797,950				-1,209,219		
2030-39	1,049,428		1,825,549	229,345	2,054,894		88,963,214	24.07
		154,702				155,024		
2040-49	1,204,130		1,963,473	246,445	2,209,918		71,115,054	19.24
		-203,751				-370,963		
2050-59	1,000,379		1,575,410	263,545	1,838,955		51,716,654	13.99
		111,015				-181,075		
2060-69	889,364		1,377,235	280,645	1,657,880		36,027,884	9.75
2070							22,149,864	5.99

[a] For any period after 1965-69 column (7) is obtained by subtracting n [column (5) - 270,078] from column (7)'s entry in the previous period. n is the number of years in the previous period and 270,078 is the mean annual recharge in acre feet.

from 1.6 million in the initial period to a peak of 3.4 million in the 1990-99 period. Then it drops to 2.8 million acres in the 2000-09 period and continues to decline from period to period until 2040, when it makes a slight recovery, and then subsides to its lowest level of 889,364 acres or 43 percent from that of the initial period. It is interesting to note that in both models the peak in the number of irrigated acres, though different in magnitude (1.6 million acres in Model I), is reached in the same time period, 1990-99.

While the minimum production goal is more than met until 2040, the irrigated acreage projected by the exponential growth model is met as a maximum only in the initial period. In the next period, 1970-79, Model II's irrigated acreage is short of the projected maximum by 6,145 acres. In the subsequent periods this shortage increases progressively as the rapidly declining water table makes some of the water resource situations uneconomical for irrigated production. Well capacity in the first saturated-thickness class (0-100 feet) declines to 42 g.p.m. at the end of the second production period, 1980-89. This means that by 1990 irrigated production is abandoned in these water resource situations, which account for 1.8 million acres or 22.74 percent of the total irrigable land, because the well capacity is inadequate to maintain irrigation systems. Water costs on the second and third saturated-thickness classes (101-200 feet and 201-300 feet) rise rather rapidly, especially for depth-to-water situations of more than 200 feet and those clay loam B and sandy loam B soils on which the water is applied by sprinkler systems. The combined effect of these factors effectively reduces the number of acres on which irrigated production is profitable as early as 1990. Since development of the exponential growth model is based on the total number of initially profitable irrigable acres, the growth in irrigated acres projected also includes the acres that have now been forced out of irrigation due to low well capacity and rising water costs. When irrigated production on these resources is set to zero, part of the projected irrigated acres that were to contribute towards the area maximum are automatically eliminated. Consequently, the model can irrigate only those portions of the projected maximum that are profitable during the period in question. Hence, Model II does not irrigate the number of acres projected by the exponential growth model after 1990. Columns (1) and (2) of Table XVII show Model II's projected irrigated acres and their period-to-period changes, respectively.

The total quantity of water withdrawn from the aquifer annually is primarily a function of the number of acres irrigated per year and, therefore, follows the same periodic trend as irrigated acres. It increases from 2.8 million acre feet in the initial period to a peak of about 6.0 million acre feet in the 1990-99 period, an increase of about 117 percent over the initial period. Except for a slight increase in the 2040-49 period, it decreases rapidly after the year 2000 to its lowest level of 1.7 million acre feet in the terminal period. The projected total annual withdrawal of ground water and its period-to-period changes are given in columns (5) and (6) of Table XVII, respectively. Columns (7) and (8), respectively, show the quantity of water in storage at the beginning of each period in absolute and relative terms. It declines precipitously from its initial level of about 370 million acre feet to about 22 million acre feet in 2070.

In Model II, the rate of decline in the water table increases from 1.55 feet per year in the 1965-69 period to a high of 3.55 feet per year and then, as the annual rate of ground water withdrawal decreases, it declines to 0.86 feet per year in the terminal period. The total water table decline by 2070 for the deeper saturated-thickness classes would be more than 215 feet, as shown in Table XVIII. As indicated in Chapter III, the use of an aerial drawdown coefficient which is higher than the coefficient of storage may bias the annual drawdown downwards and thus tend to encourage a high rate of water use as shown in Table XVII.

Concomitant to the decline in the water table, the well capacities in the six saturated-thickness classes also decline. The results of Model II, shown in Table XVIII, indicate that well capacity in the first saturated-thickness class (0-100 feet) diminishes from 500 g.p.m. in the 1965-69 period to 42 g.p.m. in 1980. Such a well capacity is too low to sustain irrigation systems and consequently irrigated production terminates on the eight water resources, WRS 1-1 through WRS 1-8. Some 1.8 million acres are involved in these resource groups and account for about 23 percent of the total irrigable land. In Model I the economic life of these water resource situations is ten years longer. In the second saturated-thickness class (101-200 feet) well capacity declines from 1,000 g.p.m. in the initial period to 19 g.p.m. by 2010. Again this level of well capacity is too low to sustain irrigation systems and, therefore, irrigated production ceases on the eight water resources, WRS 2-1 through WRS 2-8. Some 1.7 million acres or 21 percent of the total irrigable land overlie the second saturated-thickness class (101-200 feet). This implies that by 2010

TABLE XVIII

DECLINE OF THE WATER TABLE AND THE RESULTING WELL CAPACITIES OF THE SIX SATURATED THICKNESS CLASSES AS PROJECTED BY MODEL II (1965-2070)

	Water Table Decline in feet		Well Capacities in GPM[a] Saturated Thickness Class[b]					
Period	Annual	Cumulative	<100'	101-200'	201-300'	301-400'	401-500'	>500'
1965-69	1.55	-	500	1,000	1,000	1,000	1,000	1,000
1970-79	2.78	7.73	358	900	939	956	966	972
1980-89	2.91	35.52	42*	582*	736*	807	848	830
1990-99	3.55	64.62		324*	550	665*	733*	739*
2000-09	2.94	100.13		111	359	510	604	635
2010-19	2.65	129.56		19	232*	397	507	554
2020-29	1.86	156.08			141	307*	426	486
2030-39	1.11	174.70			91	251	374	441
2040-49	1.21	185.80			66	220	345*	416
2050-59	0.98	197.86			44	189	314	389
2060-69	0.86	207.62				165	290	367
2070	--	216.25				146	270	349*

[a] Indicates values at the beginning of period.

[b] Initial 1965 conditions.

*Indicate well capacities at which water costs for sprinkler systems decrease.

about 44 percent of the initial total irrigable land will not have an adequate water resource for profitable irrigation enterprises. Model I requires an additional forty years to reach this situation. In the third saturated-thickness class (201-300 feet) well capacity declines at a slower rate from 1,000 g.p.m. in the 1965-69 period to 44 g.p.m. by 2040 at which time irrigated production ceases on another 2.0 million acres. This implies that by 2050, 5.5 million acres, which account for about 68 percent of the initial irrigable land will no longer have an adequate water supply for irrigation. In Model I this situation does not occur prior to 2070. The well capacity decline in the remaining three saturated-thicknesses progresses at a much reduced rate and, consequently, the economic life of the aquifer in those water resource situations extends well beyond 2070. Unfortunately, the number of irrigable acres in these resource groups is only 2.5 million acres, which is about 32 percent of the total. Furthermore, as pump lifts increase and well capacities diminish irrigating low net return crops on some of the water situations will become uneconomical despite their continued high level of well capacity. (This is particularly important for WRS 4-3 through WRS 4-8, WRS 5-7, WRS 5-8, WRS 6-6 and WRS 6-7.) Consequently, the water resource base on which irrigation of some crops is profitable decreases even more. The combined effect of the changes discussed results in the low level of irrigated acres in later periods in spite of the higher number of total acres in the three deeper saturated-thickness classes.

Projected Annual Irrigated and Dryland Acreages, Production, and The Associated Aggregate Gross and Net Returns

In general, as Model II maximizes net returns subject to the conditions specified, irrigated acreage of each crop increases in the early periods and reaches a maximum in the 1990-99 production period. As the depletion of the ground water has its effect, the irrigated acreage of each crop declines to the minimum level in the terminal production period, 2060-69. The process is reversed for dryland acreages. They decline in the early periods as irrigation develops and then start to increase as some water resource situations are forced out of production due to rising water costs brought about by the depletion of the aquifer. As the model adjusts its production of crops in response to changing water costs, slight fluctuations in the irrigated acreage of grain sorghum, wheat, silage and alfalfa are manifested. The annual irrigated and dryland acreages of all crops as projected by Model II for all periods are presented in Table XIX. Table XX presents the irrigated and dryland production of each crop and the associated aggregate gross and net returns.

The annual irrigated acreages and production of grain sorghum, wheat, corn and alfalfa grow to about 215 percent of their 1965 level by 1990. The annual irrigated acreages and production of silage, sugar beets, cotton and soybeans grow to 205, 156, 195 and 224 percent of the initial 1965 level by 1990, respectively. In the terminal production period (2060-69), the annual irrigated acreage and production of grain sorghum drops to 48 percent. It declines to 63 percent on wheat, 75 percent on cotton, 43 percent on silage and alfalfa, 69 percent on sugar beets, 35 percent on cotton and 50 percent on soybeans.

TABLE XIX

MODEL II's PROJECTIONS OF ANNUAL IRRIGATED AND DRYLAND ACREAGES OF THE VARIOUS CROPS (1965-2070)

	Grain Sorghum		Wheat		Corn Grain	Silage	Alfalfa		Sugar Beets	Cotton		Soybeans	Total Acres	
Period	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Irrigated	Irrigated	Dryland	Irrigated	Irrigated	Dryland	Irrigated	Irrigated	Dryland
1965-69	589,569	1,091,799	849,754	5,393,038	44,516	43,584	10,270	—	5,577	876	1,179	10,792	1,554,898	6,486,016
1970-79	1,014,558	587,403	1,462,804	4,781,767	73,605	75,003	17,616	—	6,608	1,554	778	19,217	2,670,965	5,369,948
1980-89	1,055,931	787,459	1,518,704	4,472,148	79,740	77,151	18,253	—	7,638	1,656	1,351	19,875	2,778,948	5,260,958
1990-99	1,279,596	698,652	1,841,527	3,971,126	96,735	89,357	22,111	—	8,669	1,704	1,680	24,222	3,363,921	4,671,458
2000-09	1,056,003	1,018,059	1,526,322	4,221,194	83,049	78,673	18,110	—	7,890	432	5,519	19,982	2,790,461	5,244,772
2010-19	1,024,825	1,163,686	1,329,255	4,157,614	88,790	74,975	15,600	—	6,876	1,409	3,318	14,713	2,556,443	5,324,618
2020-29	590,966	1,359,937	1,120,429	4,258,304	62,007	44,921	8,918	—	6,876	846	4,838	12,415	1,847,378	5,623,079
2030-39	411,014	1,490,128	529,158	4,661,884	52,966	33,439	5,067	—	6,871	543	5,656	10,370	1,049,428	6,157,668
2040-49	449,853	1,491,195	647,974	4,506,929	52,898	34,340	6,234	19,355	3,876	538	5,668	8,417	1,204,130	6,023,147
2050-59	363,973	1,501,209	547,011	4,596,988	37,029	36,800	6,234	19,355	3,876	431	5,958	5,025	1,000,379	6,123,510
2060-69	284,976	1,501,209	538,459	4,604,828	33,377	18,585	4,373	19,355	3,876	303	6,304	5,415	889,364	6,131,696

TABLE XX

MODEL II's PROJECTION OF ANNUAL PRODUCTION OF CROPS AND THEIR AGGREGATE GROSS AND NET RETURNS (1965-2070)

Period	Grain Sorghum		Wheat		Corn Grain	Silage	Alfalfa		Sugar Beets	Cotton		Soybeans	Annual Gross Returns From		Annual Net Returns From		Total Annual Net Returns	Estimated Primary Irrigation Benefits
	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Irrigated	Irrigated	Dryland	Irrigated	Irrigated	Dryland	Irrigated	Irrigated	Dryland	Irrigated	Dryland	1,000 Dollars	1,000 Dollars
	1,000 Cwt		1,000 Bu.		1,000 Bu.	1,000 Tons	1,000 Tons		1,000 Tons	1,000 Bales		1,000 Bu.	1,000 Dollars		1,000 Dollars			
1965-69	36,553	14,958	42,035	74,424	5,787	863	77	---	112	1.2	0.6	378	136,586	131,491	49,725	44,820	94,545	23,345
1970-79	62,902	8,047	72,129	65,988	9,569	1,491	132	---	132	2.2	0.4	673	233,683	107,979	79,273	36,716	115,990	49,257
1980-89	65,468	10,788	73,629	61,716	10,366	1,534	137	---	153	2.3	0.7	696	241,826	106,379	77,726	36,246	113,972	47,710
1990-99	79,335	9,572	88,581	54,802	12,576	1,781	166	---	173	2.4	0.9	850	291,696	94,458	81,020	32,197	113,217	51,004
2000-09	65,412	13,947	72,711	58,252	10,796	1,563	136	---	158	0.6	2.9	699	241,236	106,578	57,555	36,532	94,087	27,539
2010-19	63,535	15,942	61,233	57,375	11,543	1,493	117	---	138	2.0	1.7	515	220,453	108,685	42,614	37,185	79,799	12,598
2020-29	36,640	18,631	51,329	58,765	8,061	892	67	---	138	1.2	2.5	435	153,332	115,139	30,381	39,465	69,847	365
2030-39	25,483	20,415	25,432	64,334	6,886	667	38	---	137	0.8	2.9	363	93,847	126,086	18,672	43,228	61,901	—
2040-49	27,891	20,429	28,762	62,196	6,878	686	47	30	78	0.8	3.0	295	101,690	123,720	16,690	42,237	58,928	—
2050-59	22,566	20,567	23,853	63,438	4,814	630	47	30	78	0.6	3.1	176	82,753	125,734	12,615	42,930	55,545	—
2060-69	17,668	20,567	23,573	63,546	4,339	369	33	30	78	0.4	3.3	190	72,025	125,895	10,764	42,994	53,758	—

The aggregate annual gross returns of the study area from irrigated production increases from \$136.6 million in the initial period to \$291.7 million in the 1990-99 period, an increase of about 114 percent. During the same period of time aggregate annual net income for the study area from irrigated production increases from \$49.7 million to \$81.0 million, an increase of about 63 percent. Aggregate annual gross returns from irrigation decreases to its lowest level of \$72.0 million in the 2060-69 period. This is a very substantial decrease of about \$220.0 million, or 75 percent of that by the 1990-99 period. The decline in aggregate annual net income for the same period is projected to be about \$70.3 million, or 86.7 percent. The sharpest decrease in aggregate annual net return from irrigation occurs when it drops from \$81.0 million in the 1990-99 period to \$57.6 million during the 2000-09 period which is a decline of \$23.5 million. Aggregate annual net returns from dryland enterprises decrease from the initial period until 2000 as an increasing number of dryland acres are converted to irrigated production. After 2000, irrigated acres are progressively shifted to dryland production and aggregate annual net return from dryland enterprises increases as shown in Table XX.

The primary irrigation benefits were estimated from the Model II solutions using relation (1). The assumptions of Model II permit the production of grain sorghum, wheat, alfalfa and cotton, (the crops with dryland alternatives), to such high levels that the 8.0 million cropland acres in the study area would not be adequate to produce them without irrigation after 1970. An accurate estimate of primary irrigation benefits after 1970 should be based on the maximum net returns that accrue to the dryland production of these crops on the 8.0 million cropland acres. The level of production of grain sorghum, wheat, alfalfa and cotton in 2020, which requires 7.9 million acres of cropland, (a close approximation to 8.0 million acres), is used to estimate the primary irrigation benefits in Model II. That is, after 1970 the t in relation (1) refers to the period 2020-29 in all cases except $\overline{NB}_t$ and $\overline{NR}_t$, where t refers to the period in question. The last column of Table XX indicates that the estimated annual primary irrigation benefits increase from \$23.3 million in 1965 to a peak of \$51.0 million in 1990, when irrigation development is at its highest level. Annual primary benefits decline precipitously in subsequent periods to a low of zero in 2030, reflecting the effect of the rapid depletion of the aquifer in the Model II solutions.

The irrigated cropping pattern of Model II among the 48 water resource situations is presented in Table XXI. The reference system is the same as the one used in Table XVI for Model I.

Comparison of the Results of Model I and Model II

The results of Model I and Model II exhibit similar trends over time. In both cases growth of irrigation in the study area occurs from 1965 to 2000. After the year 2000 the extent of irrigation in both models precipitously declines to its lowest level in the terminal period of 2060-69. In both cases irrigated production of crops and their associated aggregate gross and net receipts follow the same periodic trend as the growth and decline of irrigation. In both models the direction of changes in the level of underground water storage and well capacities is the same. The results differ only in magnitude and timing, which arise from differences in the basic assumptions of the

TABLE XXI

THE PATTERN OF IRRIGATED CROP PRODUCTION AMONG THE FORTY-EIGHT WATER RESOURCE SITUATIONS AS PROJECTED BY MODEL II (1965-2070)

Saturated Thickness	Depth to Water	0-50'	51-100'	101-150'	151-200'	201-250'	251-300'	301-350'	>350'
	Period	WRS 1-1	WRS 1-2	WRS 1-3	WRS 1-4	WRS 1-5	WRS 1-6	WRS 1-7	WRS 1-8
WRS 1- 0-100'	1965-69	s w c l* a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b	s w c l a b	s w c l a b	s w c l a b
	1970-79	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l a b y
	1980-89								
	1990-99								
	2000-09								
	2010-19								
	2020-29								
	2030-39								
	2040-49								
	2050-59								
	2060-69								

*See key on page 116.

TABLE XXI (Continued)

Saturated Thickness	Depth to Water Period	0-50' WRS 2-1	51-100' WRS 2-2	101-150' WRS 2-3	151-200' WRS 2-4	201-250' WRS 2-5	251-300' WRS 2-6	301-350' WRS 2-7	>350' WRS 2-8
WRS 2- 101-200'	1965-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y
	1970-79	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y
	1980-89	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c a b t y	s w c b y
	1990-99	s w c l a b t y	s w c a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c b
	2000-09	b	b	b	b	b	b	b	b
	2010-19	b	b	b	b	b	b	b	b
	2020-29								
	2030-39								
	2040-49								
	2050-59								
	2060-69								

TABLE XXI (Continued)

Saturated Thickness	Depth to Water / Period	0-50'	51-100'	101-150'	151-200'	201-250'	251-300'	301-350'	>350'
		WRS 3-1	WRS 3-2	WRS 3-3	WRS 3-4	WRS 3-5	WRS 3-6	WRS 3-7	WRS 3-8
WRS 3- 201-300'	1965-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y
	1970-79	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y
	1980-89	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y
	1990-99	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c a b t y	s w c l a b t y	s w c l a b t y	s w c a b t y	s w c l b y
	2000-09	s w c l a b t y	s w c l a b y	s w c l a b y	s w c a b y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l b y
	2010-19	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c a b t	s w c b t	w c b	c b	c b
	2020-29	w c b	w c b	b	b	b	b	b	b
	2030-39	b	b	b	b	b	b	b	b
	2040-49								
	2050-59								
	2060-69								

TABLE XXI (Continued)

Saturated Thickness	Depth to Water	0-50'	51-100'	101-150'	151-200'	201-250'	251-300'	301-350'	>350'
	Period	WRS 4-1	WRS 4-2	WRS 4-3	WRS 4-4	WRS 4-5	WRS 4-6	WRS 4-7	WRS 4-8
WRS 4- 301-400'	1965-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l a b y
	1970-79	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y
	1980-89	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b	s w c l a b y
	1990-99	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y
	2000-09	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l b y	s w c l a b	s w c l a b y
	2010-19	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c a b	s w c a b y
	2020-29	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c b t	s w c l a b t	s b	s b
	2030-39	s w c l a b t y	s w c l a b t y	s c l b t y	c l b y	c b	c b	b	b
	2040-49	s w c l a b t y	s w c l a b t y	s w c l b t y	w c l b	w c b	c b	b	b
	2050-59	s w c l a b t y	s w c l a b t y	w c l b	w c l b	w b	b	b	b
	2060-69	s w c l b y	w c l b y	w c l b	w b	w b	b	b	b

TABLE XXI (Continued)

Saturated Thickness	Depth to Water / Period	0-50'	51-100'	101-150'	151-200'	201-250'	251-300'	301-350'	>350'
		WRS 5-1	WRS 5-2	WRS 5-3	WRS 5-4	WRS 5-5	WRS 5-6	WRS 5-7	WRS 5-8
WRS 5- 401-500'	1965-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l a b y
	1970-79	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l a b y
	1980-89	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l a b y
	1990-99	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l a b y
	2000-09	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l b y	s w c l b y
	2010-19	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l b t y	s w c l b y	s w c l b y	s w c l b y	s w c l b y
	2020-29	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b y	s w c l a b
	2030-39	s w c l b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l a b	s w c l b y
	2040-49	s w c l a b y	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l b y	s w c l b y
	2050-59	s w c l a b y	s w c l a b t y	s w c l a b t	s w c l a b t y	s w c l a b y	s w c l a b y	s w c l b y	w c l b
	2060-69	s w c l a b y	s w c l a b t y	s w c l a b t	s w c l a b t y	s w c l a b y	s w c l b y	w c l b	w l b

TABLE XXI (Continued)

Saturated Thickness	Depth to Water Period	0-50' WRS 6-1	51-100' WRS 6-2	101-150' WRS 6-3	151-200' WRS 6-4	201-250' WRS 6-5	251-300' WRS 6-6	301-350' WRS 6-7	>350' WRS 6-8
WRS 6- 501-600'	1965-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l b	s w c l b	s w c l a b	
	1970-79	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b	s w c l a b	s w c l a b	
	1980-89	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b	s w c l a b	s w c l a b	
	1990-99	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b	s w c l a b	s w c l a b	
	2000-09	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l a b	s w c l a b	s w c l a b	
	2010-19	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c l b	s w c l b	s w c l b	
	2020-29	s w c l a b t y	s w c l a b t y	s w c b t y	s w c l b y	s w c l b	s w c l b	s w c b	
	2030-39	s w c l a b t y	s w c a b t y	s w c b t	s w c b	w c b	w c b	w c b	
	2040-49	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	w c a b	w c a b	w c a b	
	2050-59	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w c a b	s w a b	s w c a b	
	2060-69	s w c l a b t y	s w c l a b t y	s w c l a b t y	s w c l a b y	s w a b	s w a b	s w b	

Key: s = grain sorghum, c = corn, a = alfalfa, t = cotton
w = wheat, l = silage, b = sugar beets, y = soybeans

two models. Model I's basic assumption, that the production of the study area will not surpass its historic share of the projected national supply of the eight crops, effectively restricts a rapid growth of irrigation. Consequently, the ground water is depleted at a slower rate and most of the water resources have a longer economic life than in Model II, which assumes irrigation in the study area will grow at a somewhat slower rate than in the recent past. With no upper restriction on production of irrigated crops (except for sugar beets and cotton) this assumption enables Model II to increase the irrigated acreage of crops at a more accelerated rate than that of Model I, (compare columns (2) and (3) of Table XII with those of Table XVII), which results in a faster depletion of the water resources. These similarities and differences are borne out by a comparison of the results of the key variables of the two models as presented in Table XXII.

The first five entries, number 1, 2, ..., 5, in Table XXII are self explanatory as they have been previously discussed under the results of each model. The purpose of presenting them again is to facilitate comparison. Changes in the water costs of the two types of irrigation systems presented in entry 6 deserve some explanation and analysis. The lowest and highest total cost of water for both the initial 1965-69 period and the terminal 2060-69 period are entered for both models. Note that in the initial 1965-69 period total water costs are the same for both Model I and Model II under such system of irrigation, but that the terminal costs differ. The initial low and high water costs represent, respectively, the lowest and the highest water cost among the 48 water resource situations in the 1965-69 period. In both models the initial low water cost occurred in WRS 2-1 since it had

TABLE XXII

COMPARISON OF KEY VARIABLES IN MODEL I AND MODEL II

Item	Unit	Model I Quantity	Model I Period	Model II Quantity	Model II Period	Difference
1.Irrigated Acres[a]						
a.Maximum	acres	1,625,372	1990-99	3,363,921	1990-99	1,738,549
b.Minimum	acres	853,432	2060-69	889,364	2060-69	35,932
2.Total Water Used[a]						
a.Maximum	Ac.ft.	3,030,716	1990-99	5,969,454	1990-99	2,938,738
b.Minimum	Ac.ft.	1,835,853	2060-69	1,657,880	2060-69	177,973
3.Termination of Irrigation[1]						
a.0-100 Ft.	years	1990	1990-99	1980	1980-89	10
b.101-200 Ft.	years	2050	2050-59	2010	2010-19	40
c.201-300 Ft.	years	-	-	2050	2050-59	20+
4.Returns From Irrigation[a]						
a.Gross						
(1)Maximum	$	145,208,194	2010-19	291,695,796	1990-99	146,487,602
(2)Minimum	$	80,571,115	2060-69	72,025,219	2060-69	8,545,896
b.Net						
(1)Maximum	$	48,197,395	1990-99	81,020,387	1990-99	32,822,922
(2)Minimum	$	14,261,062	2060-69	10,764,010	2060-69	3,497,052
5.Terminal Ground Water Storage Level	Ac.ft.	124,950,914	1970	22,149,864	1970	102,801,050
6.Total Water Costs						
a.Furrow System						
(1)Initial low	$/Ac.ft.	5.28	1965-69	5.28	1965-69	----
(2)Initial high	"	17.52	1965-69	17.52	1965-69	----
(3)Terminal low	"	13.36	2060-69	14.62	2060-69	1.26
(4)Terminal high[2]	"	37.60	2060-69	43.00	2060-69	5.40
b.Sprinkler System						
(1)Initial low	$/Ac.ft.	14.16	1965-69	14.16	1965-69	----
(2)Initial high	"	26.64	1965-69	26.64	1965-69	----
(3)Terminal low	"	21.44	2060-69	26.46	2060-69	5.02
(4)Terminal high[2]	"	37.79	2060-69	41.10	2060-69	3.31

[a] Indicates figures are annual

[1] By Saturated Thickness Classes

[2] These costs represent only the highest total water cost used by activities that came into the solution of the two models in the terminal period 2060-69.

an initial well capacity of 1,000 g.p.m. and the least pump lift of 0-50 feet. The initial high water cost in both models occurred on WRS 1-8 as it has the least saturated-thickness of 0-100 feet yielding an average of 500 g.p.m. and the greatest pump lift of more than 350 feet. The terminal low water cost in both models under both irrigation systems occurrs in WRS 6-1. This is due to the fact that WRS 6-1 has the greatest initial saturated-thickness class (>500 feet) and the least pump lift (<50 feet) which enables it to maintain the highest well capacity and the lowest pump lift throughout the planning horizon (see last column of Tables XIII and XVIII), and hence, the lowest water costs. The terminal high water costs indicated in Table XXII have to be interpreted in a slightly different manner as they do not represent the highest water costs among all 48 water resource situations. By the terminal period, 2060-69, several saturated-thickness classes and their water resource situations (sixteen in Model I and twenty-four in Model II) have been completely phased out of irrigation because of the physical and economic exhaustion of their aquifers. The cost of water in these water resource situations for purposes of irrigation can be assigned a value of positive infinity to represent the condition that water for irrigation purposes is no longer available. The terminal high water costs in Table XXII refer to the highest cost of water in use. That is, they represent the highest cost paid by activities that came into the solution of the two models. Consequently, the terminal high water costs do not occur in the same water resource situation. In Model I the highest terminal total water cost in use occurs in WRS 3-8 for a surface system at a value of $37.60/ac. ft. and in WRS 4-7 for a sprinkler system at a value of $37.79/ac. ft. The initial water costs on these resources for the 1965-69 period were \$12.96/ac. ft. and \$21.12/ac. ft., respectively. If a sprinkler system was used on WRS 3-8 the total water cost would have been \$52.54/ac. ft.

In Model II the highest terminal total water cost in use occurs in WRS 4-8 for a surface system at a value of \$43.00/ac. ft. and in WRS 5-8 for a sprinkler system at a value of \$41.10/ac. ft. The initial water costs on these resources for the 1965-69 period were \$13.20/ac. ft. and \$22.56/ac. ft., respectively. Again it must be emphasized that these costs do not represent the highest water costs among the 48 water resource situations. They represent only the highest terminal total water costs in use.

In conclusion, one must note that the projections of the two models, while similar in trend, vary in the magnitude and timing of events. The assumptions incorporated in Model I result in a slower rate of development and a smaller irrigated acreage than Model II. Since no one can specify all of the information required by the models with certainty, one cannot indicate which model will approximate the actual occurrence of events in the future. Given the difference in assumptions for the two models, perhaps the most reasonable interpretation is that results of Model I represent the minimum expectations and that the results of Model II represent the maximum expectations.

At any given period in the planning horizon, the real course of events may take place between these lower and upper estimates. Any interpretation of the future from the results of the two models must be conditioned and adjusted based on what has been observed in the study area in the recent past. Nonetheless, the results of the two models offer farm operators, land owners, businessmen and policy makers a better guide to evaluate the future of their underground water reserve in the Central Ogallala Formation than a mere linear projection of the trends in the recent past.

The results in this chapter have been derived, as mentioned previously, under the assumption that irrigators acting individually will attempt to maximize their net returns to the water resource in the short run. The next chapter investigates whether the resultant annual rate of depletion of the aquifer is suboptimal as compared to the rate of depletion which maximizes the study area's net income over the entire planning horizon.

FOOTNOTES

[1] William F. Hughes and Wyatte L. Harman, *Projected Economic Life of Water Resources, Subdivision 1, High Plains Underground Water Reservoir*, Texas Agricultural Experiment Station, Texas A & M University, Texas Monograph 6 (1969).

CHAPTER V

INPUT DATA AND RESULTS OF THE SEQUENTIAL DECISION MODEL

The task of this chapter is (1) to discuss the development of the input data that are necessary to determine the optimal intertemporal allocation of ground water from the Central Ogallala Formation as a multi-stage sequential decision model capable of solution by the dynami programming technique, (2) to present the empirical results so obtained and (3) to discuss the policy implications that can be inferred from the results.

It has been shown in Chapter IV that the quantity of ground water in storage changes from period to period as the aquifer is mined over time. The various levels of ground water in storage at different points in time can be associated with corresponding levels of the water table and hence also with corresponding pumping and distribution costs of water for the various water resource situations. For any given production period the storage level at the end of the period will differ from the storage level at the beginning of the period by the amount of water that was pumped during the interim. The pumping and distribution costs of water at these two points in time are different with the water costs at the end of the production period being higher. Given constant product prices, net returns per unit of water used in the subsequent period will be less than in the period in question. This process renders the decision of how much water to withdraw from the aquifer a sequential evaluation. Given the status of the storage at any point in time, one must evaluate the effect of alternative rates of withdrawal on the total expected net returns of alternative rates of withdrawal in subsequent production periods of the planning horizon in order to make an optimal decision. Using the familiar combination formula one can readily see that a sequential evaluation of the effects of one alternative in one period on all possible alternatives in subsequent periods can mushroom to very large numbers when there are more than two alternatives and more than two periods under consideration. The power of the dynamic programming technique is that it evaluates the effects of various rates of ground water withdrawal on total expected net returns from the remaining periods in the planning horizon under all possible combinations of rates of withdrawal and all levels of ground water storage simultaneously. The technique selects the withdrawal rate for each period and each storage level that maximizes the total net returns from the remaining periods in the planning horizon provided that optimal policies of ground water withdrawal are carried on in subsequent periods. The first step in setting up the multi-stage sequential model for optimization by the dynamic programming technique is to define the component parts and specify their values as input data. These component parts, described in Chapter II, are (1) the possible input and output states of the system at all stages, (2) the sets of alternative decisions in each state, (3) the transition probabilities associated with each alternative in the set for each state and (4) the net returns that accrue to each alternative in each state.

The number of stages in the planning horizon and the appropriate discount rate to be used also need to be determined.

Assumptions in the Development of the Input Data

It has been mentioned that the net returns associated with alternative withdrawal rates play a very important role in determining the optimal rate of ground water withdrawal at each stage of the planning horizon. Any chosen alternative rate will have different net returns depending on how much water is pumped from each of the 48 water resource situations as each of them have unique water costs at any time. Ideally, the optimum rate of withdrawal for each water resource situation should be determined and aggregated for the study area. This could be accomplished in the following manner. First, the two linear programming production models (with a matrix of 840 rows by 4116 columns) would be modified to generate the net returns associated with each alternative rate of water withdrawal for each of the 48 water resource situations. Secondly, the optimum rate of withdrawal would be found for each water resource situation. This implies that 48 sequential decision models have to be constructed and run. This procedure was judged to be too cumbersome and taxing in the amount of personnel and computer time required to process the voluminous input and output data. Some simplifying assumptions must be made to circumvent this difficulty and at the same time provide a reasonable approximation to the ideal procedure.

The first simplification is to stratify the water resource situations by the six saturated-thickness classes and one weighted average depth-to-water class (see columns (1) and (2) of Table XXIV) instead of the eight depth-to-water classes. This reduces the water resource situation from 48 to six. The choice not to reduce the saturated-thickness classes was made because they determine well capacity and hence, are the principal determinants of water cost and availability. Since water costs due to lift are linear in nature, the weighted average depth introduces little or no cost bias. The six water resource situations are programmed individually using variable resource programming (parametric programming) to generate the net returns associated with each level of water made available. Two sets of models for each of the six water resource situations were used to reflect the assumptions of Model I and Model II in Chapters IV and V. These parametric programming models were not run over time as they are designed to yield conditional answers of the "if ... then" type. In other words, given various storage levels of ground water in each saturated-thickness class the models generate a set of net returns corresponding to alternative rates of ground water withdrawal irrespective of the time dimension. In the two RLP production models, it is recalled that the number of irrigated acres and/or the production restrictions change over time, thus influencing the optimal solutions. To avoid the expense of programming numerous acreage-storage level combinations, the parametric programming models assume that the number of irrigated acres and the production of crops in each saturated-thickness class will not exceed the maximum reached during the 1990-99 period in the corresponding production models I and II. That is, Model I's levels of production of the various crops for the period 1990-99 in each saturated-thickness class were made upper limits in the right hand side of the parametric models that correspond to Model I. Model II's number of irrigated acres for the period 1990-99 in each saturated-thickness class was made an upper limit in the right hand side of the parametric models that correspond to Model II. After the net returns associated with the different storage levels in each of the six saturated-thickness classes were obtained for the two sets of assumptions corresponding to Model I and Model II, the data for each saturated-thickness class was used by the sequential decision model. The name Model A is designated to refer to the sequential decision models that use data generated by the parametric programming models reflecting the assumptions of Model I. Model B refers to the sequential decision models using data generated by the parametric programming models reflecting the assumptions of Model II.

The Discrete Input and Output States

The total amount of water available in storage in 1970 in each of the six saturated-thickness classes is subdivided into a convenient set of discrete intervals which are designated as input states S_i and output states S_j. Table XXIII shows the number of these states in each saturated-thickness class and the range of ground water storage level they represent in both models A and B. Note that the size of the class interval for the states is not the same in all saturated-thickness classes. It was chosen on the basis of the maximum use rate of water permitted by the upper limit on crop production and/or irrigated acreage restrictions imposed on the two types of parametric programming models and the magnitude of changes in water costs from one state to the next. Since the rate of water use is more conservative in Model A, the states in the first saturated-thickness class (0-100 feet) have an interval of only one million acre feet. In the next four saturated-thickness classes the class interval of the states is a wider 5 million

TABLE XXIII

DISCRETE INTERVALS OF GROUND WATER STORAGE LEVELS DESIGNATING THE VARIOUS STATES OF EACH SATURATED THICKNESS CLASS IN THE SEQUENTIAL DECISION MODELS A AND B[1]

State	Saturated Thickness Class					
S_i or S_j	0-100'	101-200'	201-300'	301-400'	401-500'	>500'
	Storage of Ground Water in Million Ac. Ft.					
1	19.1-20.0	53.0-57.0	104.0-108.0	98.0-102.0	44.0-48.0	31.1-33.0
2	18.1-19.0	47.0-52.0	99.0-103.0	93.0-97.0	39.0-43.0	29.1-31.0
3	17.1-18.0	43.0-46.0	94.0-98.0	88.0-92.0	34.0-38.0	27.1-29.0
4	16.1-17.0	38.0-42.0	89.0-93.0	83.0-87.0	29.0-33.0	25.1-27.0
5	15.1-16.0	33.0-37.0	84.0-88.0	78.0-82.0	24.0-28.0	23.1-15.0
6	14.1-15.0	28.0-32.0	79.0-83.0	73.0-77.0	19.0-23.0	21.1-23.0
7	13.1-14.0	23.0-27.0	74.0-78.0	68.0-72.0	14.0-18.0	19.1-21.0
8	12.1-13.0	18.0-22.0	69.0-73.0	63.0-67.0	9.0-13.0	17.1-19.0
9	11.1-12.0	13.0-17.0	64.0-68.0	58.0-62.0	0.0-8.0	15.1-17.0
10	10.1-11.0	8.0-12.0	59.0-63.0	53.0-57.0		13.1-15.0
11	9.1-10.0	0.0-7.0	54.0-58.0	48.0-52.0		11.1-13.0
12	0.0-9.0		49.0-43.0	43.0-47.0		9.1-11.0
13			44.0-48.0	38.0-42.0		7.1-9.0
14			39.0-43.0	33.0-37.0		5.1-7.0
15			34.0-38.0	28.0-32.0		0.0-5.0
16			29.0-33.0	23.0-27.0		
17			24.0-28.0	18.0-22.0		
18			19.0-23.0	13.0-17.0		
19			0.0-19.0	0.0-12.0		

[1] In Model B saturated thickness classes 0-100' and >500' have a smaller number of states. Since water use is higher in these WRS's under the optimal solutions of Model II, the class interval of their states is made 5 million acre feet (vs. 1 and 2 million acre feet for saturated thiskness class 0-100' and >500' in Model I) resulting in a smaller number of states.

acre feet as water costs change at a slower rate and use rates of water are high. The sixth saturated-thickness class (>500 feet) possesses less than five percent of the total irrigable area limiting the extent of irrigated activity. The maximum use rate of water in this water resource situation can be only 2.5 million acre feet per year in Model I. The class interval of its states is two million acre feet. The number of states in each water situation was determined by the storage level that limits well capacities to such a level that irrigation systems can not be sustained. The storage levels of the last state in each saturated-thickness class represents such a situation.

In Model B the number of states and their class intervals are the same as in Model A for all saturated-thickness classes except 0-100 feet and >500 feet. Water use is high in these water resource situations under the optimal solutions of Model II and the class interval of their states is increased to five million acre feet for Model B. According to this classification there are only four states in saturated-thickness class 0-100 feet -- namely,

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{bmatrix} = \begin{bmatrix} 16\text{-}20 \\ 11\text{-}16 \\ 6\text{-}10 \\ 0\text{-}5 \end{bmatrix} \text{ million acre feet}$$

and seven states in saturated-thickness class >500 feet -- namely,

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ S_7 \end{bmatrix} = \begin{bmatrix} 29\text{-}33 \\ 24\text{-}28 \\ 19\text{-}23 \\ 14\text{-}18 \\ 9\text{-}13 \\ 4\text{-}8 \\ 0\text{-}4 \end{bmatrix} \text{ million acre feet.}$$

The Discrete Alternative Rates of Ground Water Withdrawal

The number of discrete annual rates of ground water withdrawal, their range of values in the states to which they belong and the amount by which successive rates are incremented are shown for each water resource situation in Table XXIV for both Model A and Model B. The annual rates of withdrawal were determined by experimentation in conjunction with the class size of the states and the maximum ground water use permitted by the crop production and/or acreage restrictions imposed on the corresponding parametric programming models. The information in the first row of Table XXIV indicates the first saturated-thickness class has ten alternative annual rates of ground water withdrawal for each state of Model A ranging from zero to 0.45 million acre feet by successive increments of 0.05 million acre feet. In Model B the first saturated-thickness class has 11 alternative annual rates of ground water withdrawal for each state ranging from zero to one million acre feet by successive increments of 0.1 million acre feet. The rest of the data in Table XXIV for the remaining water resource situations can be interpreted in a similar fashion. Note that in Model B the ranges

TABLE XXIV

ALTERNATIVE ANNUAL RATES OF GROUND WATER WITHDRAWAL IN EACH STATE OF THE SIX SATURATED THICKNESS CLASSES IN THE SEQUENTIAL DECISION MODELS A AND B

Saturated Thickness Class (1)	Weighted Average Depth (2)	Range of Alternative Annual Rates of Ground Water Withdrawal (3)		Increment in Successive Rates of (3) (4)		Number of Alternative Annual Rates of Ground Water Withdrawal (5)	
in ft.	in ft.	in mill. ac. ft.		in mill. ac. ft.		in mill. ac. ft.	
		Model A	Model B	Model A	Model B	Model A	Model B
0-100	119	0-0.45	0-1.00	0.05	0.10	10	11
101-200	159	0-0.90	0.1.50	0.10	0.10	10	16
201-300	161	0-0.90	0-2.10	0.10	0.10	10	22
301-400	148	0-0.90	0-1.20	0.10	0.10	10	13
401-500	142	0-0.30	0-0.70	0.10	0.10	4	8
Over 500	118	0-0.25	0-0.40	0.05	0.10	6	5

permit higher rates of ground water withdrawal reflecting the extensive use of water in the second production model of the previous chapters.

The Transition Probabilities

The elements of the transition probabilities matrix for each set of alternative rates of ground water withdrawal in each input state define the probability that the state will occupy a certain output state at the end of a stage via each alternative decision taken in that stage. In this study the multi-stage decision process is formulated as a deterministic case and, therefore, the elements of the probability matrix are either one or zero. The reason for making the multi-stage decision process nonstochastic is due to the relative smallness of the relevant random variable, annual recharge, with respect to the magnitude of the class interval of the states. The average annual recharge for the entire area is about 0.27 million acre feet per year while the smallest class interval of the states in the six water resource situation aggregates to 23 million acre feet. This implies that recharge would have to be 85 times the estimated amount to increase the ground water storage level one state. The highest total annual precipitation recorded during the 25-year period of 1941-1965 was about 31 inches. Annual recharge from this amount of yearly precipitation will amount to only 0.46 million acre feet, which is not sufficient to affect the status of any state. The minimum value recharge can have is zero and the absence of recharge will not transfer any given state to a lower one. In the absence of large streams recharging the Central Ogallala Formation the range of variation in precipitation will not significantly alter the ground water storage level within the framework of the classification of the input and output states of the system. Because the estimated demand of ground water for municipal and industrial purposes averages about 0.21 million acre feet per year, it can be assumed that the average annual recharge will satisfy this demand. Consequently, both the recharge component and the industrial and municipal ground water demand component can be omitted in the multi-stage sequential decision models.

With these assumptions the input states at any stage of the system are transformed to other output states only by the magnitude of the rate of ground water withdrawal considered to be optimal for that stage. Since these decisions are known with certainty and the transformations are performed _ex post_ for the next stage, the multi-stage sequential decision model can be formulated as a nonstochastic process. In other words, given the state of the process at the beginning of any stage and the optimal decision on the rate of withdrawal, the output state of the system for the next stage is unique. Since there are 12 formulations of the system, two formulations each representing Model A and Model B for the six water resource situations, presenting all of the transition probability matrices is a lengthy process. Therefore, saturated-thickness class 401-500 feet for Model B is chosen to serve as an illustration of how the transition probabilities were constructed in each of the 12 formulations. Table XXV shows nine sets of transition probabilities, one set for each state. An interpretation of the data presented is as follows.

Suppose the system is in input state S_1 at the beginning of a given stage, there are eight alternative rates of ground water withdrawal ranging from zero to seven million acre feet per stage to choose

TABLE XXV

THE TRANSITION PROBABILITY MATRIX FOR SATURATED THICKNESS CLASS 401-500 FT. IN MODEL B

Input State at the Beginning of a Stage S_i	Storage Level mill. ac. ft.	Alternative Rate of Withdrawal per Stage W_k	mill. ac. ft.	Output State at the End of a Stage S_j 1	2	3	4	5	6	7	8	9
				Transition Probabilities P_{ij}^k								
1	44-48	1	0	1	0	0	0	0	0	0	0	0
		2	1	1	0	0	0	0	0	0	0	0
		3	2	1	0	0	0	0	0	0	0	0
		4	3	1	0	0	0	0	0	0	0	0
		5	4	1	0	0	0	0	0	0	0	0
		6	5	0	1	0	0	0	0	0	0	0
		7	6	0	1	0	0	0	0	0	0	0
		8	7	0	1	0	0	0	0	0	0	0
2	39-43	1	0	0	1	0	0	0	0	0	0	0
		2	1	0	1	0	0	0	0	0	0	0
		3	2	0	1	0	0	0	0	0	0	0
		4	3	0	1	0	0	0	0	0	0	0
		5	4	0	1	0	0	0	0	0	0	0
		6	5	0	0	1	0	0	0	0	0	0
		7	6	0	0	1	0	0	0	0	0	0
		8	7	0	0	1	0	0	0	0	0	0
3	34-38	1	0	0	0	1	0	0	0	0	0	0
		2	1	0	0	1	0	0	0	0	0	0
		3	2	0	0	1	0	0	0	0	0	0
		4	3	0	0	1	0	0	0	0	0	0
		5	4	0	0	1	0	0	0	0	0	0
		6	5	0	0	0	1	0	0	0	0	0
		7	6	0	0	0	1	0	0	0	0	0
		8	7	0	0	0	1	0	0	0	0	0

TABLE XXV (Continued)

Input State at the Beginning of a Stage S_i	Storage Level mill. ac. ft.	Alternative Rate of Withdrawal per Stage W_k	mill. ac. ft.	Output State at the End of a Stage S_j Transition Probabilities P_{ij}^k								
				1	2	3	4	5	6	7	8	9
4	29-33	1	0	0	0	0	1	0	0	0	0	0
		2	1	0	0	0	1	0	0	0	0	0
		3	2	0	0	0	1	0	0	0	0	0
		4	3	0	0	0	1	0	0	0	0	0
		5	4	0	0	0	1	0	0	0	0	0
		6	5	0	0	0	0	1	0	0	0	0
		7	6	0	0	0	0	1	0	0	0	0
		8	7	0	0	0	0	1	0	0	0	0
5	24-28	1	0	0	0	0	0	1	0	0	0	0
		2	1	0	0	0	0	1	0	0	0	0
		3	2	0	0	0	0	1	0	0	0	0
		4	3	0	0	0	0	1	0	0	0	0
		5	4	0	0	0	0	1	0	0	0	0
		6	5	0	0	0	0	0	1	0	0	0
		7	6	0	0	0	0	0	1	0	0	0
		8	7	0	0	0	0	0	1	0	0	0
6	19-23	1	0	0	0	0	0	0	1	0	0	0
		2	1	0	0	0	0	0	1	0	0	0
		3	2	0	0	0	0	0	1	0	0	0
		4	3	0	0	0	0	0	1	0	0	0
		5	4	0	0	0	0	0	1	0	0	0
		6	5	0	0	0	0	0	0	1	0	0
		7	6	0	0	0	0	0	0	1	0	0
		8	7	0	0	0	0	0	0	1	0	0

TABLE XXV (Continued)

Input State at the Beginning of a Stage S_i	Storage Level mill. ac. ft.	Alternative Rate of Withdrawal per Stage W_k	mill. ac. ft.	Output State at the End of a Stage S_j								
				1	2	3	4	5	6	7	8	9
				Transition Probabilities P_{ij}^k								
7	14-18	1	0	0	0	0	0	0	0	1	0	0
		2	1	0	0	0	0	0	0	1	0	0
		3	2	0	0	0	0	0	0	1	0	0
		4	3	0	0	0	0	0	0	1	0	0
		5	4	0	0	0	0	0	0	1	0	0
		6	5	0	0	0	0	0	0	0	1	0
		7	6	0	0	0	0	0	0	0	1	0
		8	7	0	0	0	0	0	0	0	1	0
8	9-13	1	0	0	0	0	0	0	0	0	1	0
		2	1	0	0	0	0	0	0	0	1	0
		3	2	0	0	0	0	0	0	0	1	0
		4	3	0	0	0	0	0	0	0	1	0
		5	4	0	0	0	0	0	0	0	1	0
		6	5	0	0	0	0	0	0	0	0	1
		7	6	0	0	0	0	0	0	0	0	1
		8	7	0	0	0	0	0	0	0	0	1
9	0-8	1	0	0	0	0	0	0	0	0	0	1
		2	1	0	0	0	0	0	0	0	0	1
		3	2	0	0	0	0	0	0	0	0	1
		4	3	0	0	0	0	0	0	0	0	1
		5	4	0	0	0	0	0	0	0	0	1
		6	5	0	0	0	0	0	0	0	0	1
		7	6	0	0	0	0	0	0	0	0	1
		8	7	0	0	0	0	0	0	0	0	1

from. If any one of the alternatives W_1 through W_5 is chosen as the optimal policy, the output of the system will still be in S_1 at the end of the stage because the probability associated with each of them is one. If on the other hand any of the alternatives W_6 through W_8 is chosen as the optimal policy, the state of the system will transit to output state S_2 at the end of that stage. The rest of the probabilities for the remaining states are interpreted in a similar fashion. Using Tables XXIII and XXIV as a guide one can visualize how the probability matrices for each of the water resource situations are constructed.

The Stage Returns

The stage return constitutes the criterion by which the multistage decision model selects the optimal policy. The rate of withdrawal that contributes the most to the expected discounted net returns for each rate of ground water withdrawal in each state was generated from the results of the parametric programming models discussed earlier in this chapter. Presentation of the net returns data from each of the 12 formulations would be a lengthy process. To conserve space, input data for the one saturated-thickness class, 401-500 feet, for Model B are presented in Table XXVI. This set of net returns is associated with the matrices of transition probabilities given in Table XXV. When no ground water is withdrawn, alternative W_1, the dryland net return of $4.13 million is common to all storage levels. For any storage level greater than W_1, reading down Table XXVI column-wise, note that the net returns decrease reflecting the effects of increasing water costs from one input state to the next. For any given input state, reading across Table XXVI row-wise, note that the differences

TABLE XXVI

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 401-500 FT. IN MODEL B

Input State S_1	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in million ac. ft. 0	1	2	3	4	5	6	7
		Undiscounted Annual Net Returns in Million Dollars							
1	44-48	4.13	6.81	9.18	11.50	13.55	15.38	16.91	18.31
2	39-43	4.13	6.79	9.15	11.44	13.48	15.31	16.83	18.21
3	34-38	4.13	6.78	9.11	11.39	13.41	15.23	16.73	18.10
4	29-33	4.13	6.76	9.07	11.33	13.34	15.04	16.51	17.85
5	24-28	4.13	6.72	8.99	11.19	13.15	14.89	16.33	17.65
6	19-23	4.13	6.68	8.92	11.08	13.01	14.54	15.91	17.17
7	14-18	4.13	6.60	8.76	10.81	12.66	14.13	15.43	16.60
8	9-13	4.13	6.50	8.59	10.51	12.27	13.77	14.99	16.11
9	0-8	4.13	-[a]	-	-	-	-	-	-

[a] (-) entries indicate that net returns will be negative if those decisions are made in the corresponding state.

between net returns of successive alternatives get smaller and smaller. In other words, while the rate of increase in the ground water withdrawn is the same between successive alternatives, the rate of increase in the corresponding net returns is decreasing indicating diminishing returns exist in applying larger and larger quantities of ground water. In input state, S_9, any withdrawal of ground water results in negative net returns. The net returns generated from the parametric programming models for the remaining water resource situations are given in Appendix G, Tables XLVI-LVI.

The Planning Horizon and the Discount Rate

The planning horizon has been arbitrarily selected to be the 100 year period from 1970-2070. In the formulation of the sequential decision model the planning horizon is divided into ten ten-year intervals defining the ten stages of the system. Stage one represents the production period 1970-79, stage two represents 1980-89, etc. to stage ten which represents the production period 2060-69.

The rate of ground water withdrawal selected as optimal for each state in a given stage represents the sum of ten equal annual rates. However, the same cannot be said of the associated stage returns. As the stages represent a ten-year interval at different points in the planning horizon, the net return attributed to the first year of a given stage is not of the same value as that attributed to the tenth year. To make them comparable, the net returns of each of the ten years are discounted to their present values at the beginning of the stage. More important is making the net returns of the tenth stage comparable to those of the first stage. The use of a discount factor implies that net returns expected to accrue in time periods near to the present are of greater consequence in decision making than net returns of equal magnitude in distant time periods. The net returns in all time periods of the planning horizon are made comparable by applying an appropriate interest rate and discounting procedure.

The selection of an appropriate discount rate is important. Too low a discount rate may discourage present use of ground water. On the other hand, too high a discount rate may discourage saving ground water for future use. Since ground water is developed by the private capital of farmers, the relevant discount rate may be narrowed to the selection from the interest rates farmers face. These rates range from those on production credit in agriculture to rates on personal savings of farmers or the rate of return on fixed capital (asset equity) in farm production. It is clear that there is no one single value for the discount rate. In this study, three discount rates, $r = 0.00$, $r = 0.04$, and $r = 0.08$, are used to test the sensitivity of the optimal solution. The procedure used to discount the various net returns within a stage and between stages is given by the following relation:

$$\begin{aligned} PV = {} & R_1 \frac{1 - (1 + r)^{-n}}{r} + R_2 \frac{1 - (1 + r)^{-n}}{r} (1 + r)^{-n} \\ & + R_3 \frac{1 - (1 + r)^{-n}}{r} (1 + r)^{-2n} + \ldots \\ & + R_m \frac{1 - (1 + r)^{-n}}{r} (1 + r)^{-n(m-1)} \\ & + \ldots + R_{10} \frac{1 - (1 + r)^{-n}}{r} (1 + r)^{-9n} \end{aligned} \qquad (1)$$

Where:

PV = the expected present value of the stream of net returns from all stages in the planning horizon,

$m = 1, 2, \ldots, 10$ is the m^{th} stage,

$n = 10$ is the number of years in each stage,

R_m = the annual net return attributed to the optimal annual rate of ground water withdrawal in stage m,

r = the discount rate used,

$\frac{1 - (1 + r)^{-n}}{r}$ = the annuity of a net return of $1.00 for n years at a discount rate of r, and

$(1 + r)^{-n(m-1)}$ = the present value formula for the m^{th} stage.

There are three factors in each term of the series in relation (1), namely, R_m, the annuity formula, and the present value formula. The annuity formula discounts the stream of equal annual net returns, R_m, to the beginning of the stage and sums the ten years of each stage. The present value formula discounts the expected total net return of each stage back to the beginning of the planning horizon. In the first term of relation (1), the present value formula is implicit because it reduces to one as m-1 is equal to zero.

Solutions of the Multi-Stage Sequential Decision Models

The multi-stage decision models for each of the six saturated-thickness classes under the two assumptions of Model A and Model B were optimized using the dynamic programming technique. The computer algorithm developed for the technique follows Howard's "value iterative" method.[1] Three sets of solutions were obtained for each water resource situation under Model A and Model B. For the sake of brevity, only one solution using the 0.04 discount rate for saturated-thickness class 401-500 feet under the assumptions of Model B is shown in Tables XXVII and XXVIII. Note that this solution corresponds to the transition probabilities and net returns given in Tables XXV and XXVI, respectively. The optimal policies and their corresponding maximum expected discounted net returns are conditional for every possible input state of the system in each stage. To map the optimal policy to be followed through the ten stages of the planning horizon, one must start at the beginning of stage one and proceed step by step to stage ten. In saturated-thickness 401-500 feet, the input state in stage one is 47 million acre feet which falls in input state S_1. The optimal policy, as shown in Table XXVII, is to withdraw seven million acre feet of water during the first ten years. This reduces the supply of ground water in storage to 40 million acre feet which transforms the system to output state S_2 at the end of stage one. This implies that the input state of the system at the beginning of stage two is S_2. The optimal policy in stage two when the system is in S_2 is again to withdraw seven million acre feet which reduces the supply in storage to 33 million acre feet thus transforming the system to output state S_4 at the end of the second stage. At the beginning of stage three the input state of the system is S_4. Following this procedure one can trace the movement of the system from stage to stage and map the optimum strategy for allocating the ground water over the planning horizon. The asterisks in Table XXVII indicate the input state of the system, the optimal rate of ground water withdrawal and the resulting output of the system for the ten stages of the planning horizon. Table XXVIII shows

TABLE XXVII

SOLUTION OF THE MULTISTAGE SEQUENTIAL DECISION MODEL: OPTIMAL RATES OF GROUND WATER WITHDRAWAL FOR SATURATED THICKNESS 401-500 FT. MODEL B, r = 0.04

State of the System S_i	Storage Level mill. ac. ft.	Stage in the Planning Horizon									
		1	2	3	4	5	6	7	8	9	10
		Optimal Rates of Ground Water Withdrawal in million ac. ft.									
1	44-48	7*	7	7	7	7	7	7	7	7	7
2	39-43	7	7*	7	7	7	7	7	7	7	7
3	34-38	7	7	7	7	7	7	7	7	7	7
4	29-33	7	7	7*	7	7	7	7	7	7	7
5	24-28	7	7	7	7*	7	7	7	7	7	7
6	19-23	7	7	7	7	7*	7	7	7	7	7
7	14-18	7	7	7	7	7	7	7	7	7	7
8	9-13	4	4	4	4	4	4*	4	4	4	7
9	0-8	0	0	0	0	0	0	0*	0*	0*	0*

TABLE XXVIII

SOLUTION OF THE MULTISTAGE SEQUENTIAL DECISION MODEL MAXIMUM EXPECTED DISCOUNTED NET RETURNS CORRESPONDING TO THE OPTIMAL DECISIONS FOR SATURATED THICKNESS 401-500 FT. MODEL B, $r = 0.04^a$

State of the System S_i	Storage Level mill. ac. ft.	Stage in the Planning Horizon									
		1	2	3	4	5	6	7	8	9	10
		Total Expected Discounted Net Returns in Mill. Dollars									
1	44-48	436.6*	434.2	430.5	422.1	409.3	389.7	359.9	315.2	248.2	148.5
2	39-43	429.0	426.5*	422.9	417.4	405.0	386.0	357.0	312.9	246.8	147.7
3	34-38	418.9	416.4	412.8	407.3	399.3	380.9	352.8	309.9	244.6	146.8
4	29-33	405.3	402.8	399.1*	393.7	385.7	373.7	346.5	305.0	241.4	144.7
5	24-28	388.1	385.6	382.0	376.5*	368.5	356.6	339.0	299.0	237.2	143.1
6	19-23	365.1	362.6	358.9	353.5	345.5*	333.6	316.0	290.0	230.2	139.2
7	14-18	336.8	334.3	330.6	325.2	317.2	305.3	287.6	261.6	223.0	134.7
8	9-13	301.6	299.1	295.5	290.0	282.0	270.1*	252.5	226.4	187.8	130.7
9	0-8	101.3	100.3	98.9	96.7	93.5	88.8	81.8*	71.5*	56.2*	33.5*

[a] The maximum expected net returns refers to the entire planning horizon provided that optimal policies are followed in the remaining stages.

the maximum discounted net returns that can be expected from the current and remaining stages provided that an optimal policy is followed at each subsequent stage. The values with asterisks are the maximum expected discounted net returns corresponding to the optimal policies also shown by asterisks in Table XXVIII.

The optimal rates of ground water withdrawal at each stage for the six water resource situations using each of the three discount rates were traced by the procedure described above. The optimal policies and their corresponding maximum expected net returns for the current and remaining stages are presented in Table XXIX for both Model A and Model B. The results are also aggregated for the study area.

At any given stage of the planning horizon, there are economic forces working in opposite directions. Increased costs of pumping and distributing water for the remaining stages in the planning horizon tend to discourage high rates of ground water withdrawal in the current stage. Diminishing marginal net returns to water set in at high rates of water use, particularly if the storage level is low, which again tends to reduce the optimal rate of ground water withdrawal per stage. On the other hand, higher preference for income in the early stages of the planning horizon as reflected by the discount factor and increasing marginal returns to additional rates of water, particularly when storage levels are high and withdrawal rates are low, tend to increase the optimal rates of withdrawal per stage. The fact that high storage levels are encountered at the stages toward the beginning of the planning horizon tend to reinforce the time preference effect and thus intensify the optimal ground water withdrawal rates in the early periods. The results tabulated in Table XXIX are the net effects of

TABLE XXIX

OPTIMAL POLICIES OF GROUND WATER WITHDRAWAL AND THEIR EXPECTED DISCOUNTED NET RETURNS ACCORDING TO THE SOLUTIONS OF THE MULTISTAGE SEQUENTIAL DECISION MODELS A AND B AT THREE DISCOUNT RATES

				Model A								Model B							
					Saturated Thickness in Ft.								Saturated Thickness in Ft.						
Stage	Discount at r =	Item	Unit	Study Area Level of Storage	0-100	101-200	201-300	301-400	401-500	>500	Total Study Area	Study Area Level of Storage	0-100	101-200	201-300	301-400	401-500	>500	Total Study Area
1 (1970-79)	0.00	Rate of Withdrawal	mill.Ac.Ft.	358.0	3.5	4.0	9.0	8.0	3.0	1.5	29.0	357.0	4.0	4.0	9.0	4.0	4.0	4.0	29.0
		Expected Discounted Net Income	mill. dol.		2,326.510	2,159.260	2,531.730	2,867.29	789.580	514.360	10,388.73		2,223.549	3,000.479	3,996.594	2,439.528	1,671.023	1,176.799	14,507.972
	0.04	Rate of Withdrawal	mill.Ac.Ft.	358.0	3.5	9.0	9.0	8.0	3.0	2.0	34.5	357.0	9.0	14.0	19.0	12.0	7.0	4.0	65.0
		Expected Discounted Net Income	mill. dol.		398.946	551.554	626.648	512.054	193.504	126.699	2,409.405		557.285	1,806.455	2,542.246	1,473.613	436.647	643.975	7,540.221
	0.08	Rate of Withdrawal	mill.Ac.Ft	358.0	4.5	9.0	9.0	8.0	3.0	2.0	35.5	357.0	9.0	14.0	21.0	12.0	7.0	4.0	67.0
		Expected Discounted Net Income	mill. dol.		234.527	284.841	320.410	261.939	98.635	64.871	1,265.223		294.482	1,710.961	2,276.122	1,276.472	227.058	543.889	6,328.976
		RLP Rate of Withdrawal	mill.Ac.Ft.	358.0	2.3	5.56	9.41	6.55	2.5	2.18	26.43	357.0	10.44	9.82	11.29	9.15	3.39	2.01	46.10
2 (1980-89	0.00	Rate of Withdrawal	mill.Ac.Ft.	329.0	3.5	4.0	9.0	8.0	3.0	1.5	29.0	328.0	4.0	4.0	9.0	4.0	4.0	4.0	29.0
		Expected Discounted Net Income	mill. dol.		2,104.660	1,928.820	2,262.170	1,848.030	710.620	463.220	9,317.520		2,005.717	2,670.156	3,543.732	2,224.593	1,406.413	1,059.119	12,989.730
	0.04	Rate of Withdrawal	mill.Ac.Ft.	323.5	3.5	9.0	9.0	8.0	3.0	2.0	34.5	292.0	9.0	14.0	19.0	12.0	7.0	4.0	65.0
		Expected Discounted Net Income	mill. dol.		370.862	533.168	616.534	503.698	191.626	124.999	2,341.287		528.512	1,700.634	2,371.897	1,434.740	426.520	637.726	7,100.829
	0.08	Rate of Withdrawal	mill.Ac.Ft.	323.5	3.5	9.0	9.0	8.0	3.0	2.0	34.5	290.0	9.0	14.0	19.0	12.0	7.0	4.0	65.0
		Expected Discounted Net Income	mill. dol.		200.723	280.001	318.677	260.233	98.583	64.605	1,222.822		278.147	1,597.770	2,197.119	1,263.653	224.964	543.602	6,105.255
		RLP Rate of Withdrawal	mill.Ac.Ft.	331.6	0.40	6.19	8.80	7.63	2.80	2.45	27.91	310.90	0.004	13.28	15.19	12.27	4.56	2.71	47.934

TABLE XXIX (Continued)

Stage	Discount at r =	Item	Unit	Study Area Level of Storage	Model A							Study Area Level of Storage	Model B						
					Saturated Thickness in Ft. 0-100	101-200	201-300	301-400	401-500	>500	Total Study Area		Saturated Thickness in Ft. 0-100	101-200	201-300	301-400	401-500	>500	Total Study Area
3 (1990-99)	0.00	Rate of Withdrawal	mill.Ac.Ft.	300.0	0.5	4.0	9.0	8.0	3.0	1.5	26.0	299.0	4.0	4.0	9.0	4.0	4.0	4.0	29.0
		Expected Discounted Net Income	mill. dol.		988.400	1,699.410	1,989.410	1,638.990	627.82	410.51	7,354.54		1,742.907	2,340.833	3,092.395	1,998.776	1,351.609	930.477	11,456.997
	0.04	Rate of Withdrawal	mill.Ac.Ft.	289.0	1.5	9.0	9.0	8.0	3.0	2.0	32.5	227.0	0.0	9.0	19.0	12.0	7.0	4.0	51.0
		Expected Discounted Net Income	mill. dol.		315.340	505.200	602.690	494.599	187.697	122.692	2,228.218		282.381	1,407.962	2,116.662	1,378.100	399.122	621.157	6,205.384
	0.08	Rate of Withdrawal	mill.Ac.Ft.	289.0	1.5	9.0	9.0	8.0	3.0	2.0	32.5	225.0	0.0	9.0	19.0	12.0	7.0	4.0	51.0
		Expected Discounted Net Income	mill. dol.		154.082	271.388	315.904	259.053	97.871	64.282	1,162.580		147.272	1,315.854	2,033.828	1,239.978	217.234	536.660	5,490.826
		RLP Rate of Withdrawal	mill.Ac.Ft.	303.7	0.43	6.13	8.60	8.64	3.30	2.24	29.34	263.0	0.0	15.95	18.44	14.86	5.54	3.29	58.08
4 (2000-29	0.00	Rate of Withdrawal	mill.Ac.Ft.	274.0	0.5	4.0	9.0	8.0	3.0	1.5	26.0	270.0	4.0	4.0	9.0	12.0	4.0	4.0	37.0
		Expected Discounted Net Income	mill. dol.		864.85	1,502.730	1,719.800	1,419.920	549.340	358.180	6,414.820		1,467.228	2,120.632	2,642.508	1,837.241	1,116.857	806.495	9,990.961
	0.04	Rate of Withdrawal	mill.Ac.Ft.	256.5	0.0	9.0	9.0	8.0	3.0	2.0	31.0	176.0	0.0	9.0	14.0	12.0	7.0	4.0	46.0
		Expected Discounted Net Income	mill. dol.		252.137	479.798	582.789	478.846	183.608	119.517	2,096.695		276.229	1,259.907	1,751.600	1,307.130	376.522	601.898	5,573.286
	0.08	Rate of Withdrawal	mill.Ac.Ft.	256.5	0.0	9.0	9.0	8.0	3.0	2.0	31.0	174.0	0.0	9.0	14.0	12.0	7.0	4.0	46.0
		Expected Discounted Net Income	mill. dol.		134.000	262.595	311.710	255.745	97.631	63.875	1,125.887		146.909	1,193.440	1,793.134	1,212.381	210.465	530.295	5,016.624
		RLP Rate of Withdrawal	mill.Ac.Ft.	274.4	0.0	3.27	6.99	9.41	3.75	1.43	24.85	204.9	0.0	0.01	21.05	16.87	6.34	3.76	48.03

TABLE XXIX (Continued)

Stage	Discount at r =	Item	Unit	Study Area Level of Storage	Model A							Study Area Level of Storage	Model B						
					Saturated Thickness in Ft.						Total Study Area		Saturated Thickness in Ft.						Total Study Area
					0-100	101-200	201-300	301-400	401-500	>500			0-100	101-200	201-300	301-400	401-500	>500	
5 (2010-19)	0.00	Rate of Withdrawal	mill.Ac.Ft.	248.0	0.0	4.0	9.0	8.0	3.0	1.5	25.5	233.0	0.0	4.0	9.0	12.0	4.0	4.0	33.0
		Expected Discounted Net Income	mill. dol.		646.61	1,276.130	1,467.400	1,213.440	468.220	306.000	5,377.800		703.942	1,793.434	2,291.160	1,509.361	987.131	681.469	7,966.497
	0.04	Rate of Withdrawal	mill.Ac.Ft.	225.5	0.0	9.0	9.0	8.0	3.0	2.0	31.0	130.0	0.0	0.0	14.0	12.0	7.0	4.0	37.0
		Expected Discounted Net Income	mill. dol.		243.825	433.737	559.612	460.893	176.556	114.940	1,989.563		267.123	604.566	1,478.545	1,177.572	345.467	573.795	4,447.068
	0.08	Rate of Withdrawal	mill.Ac.Ft.	225.5	0.0	9.0	9.0	8.0	3.0	2.0	31.0	128.0	0.0	0.0	14.0	12.0	7.0	4.0	37.0
		Expected Discounted Net Income	mill. dol.		133.356	241.720	307.950	253.080	96.565	63.142	1,095.813		146.127	547.868	1,282.532	1,142.872	198.741	519.983	3,838.123
		RLP Rate of Withdrawal	mill.Ac.Ft.	249.5	0.0	3.7	8.02	9.24	3.77	1.67	26.40	156.9	0.0	0.0	14.88	17.54	6.84	4.14	43.40
6 (2020-29)	0.00	Rate of Withdrawal	mill.Ac.Ft.	222.5	0.0	0.0	9.0	8.0	3.0	1.5	21.5	200.0	0.0	4.0	14.0	12.0	4.0	4.0	38.0
		Expected Discounted Net Income	mill. dol.		538.840	1,049.470	1,200.370	997.32	387.80	255.30	4,429.100		590.329	1,468.279	1,841.480	1,236.042	806.857	547.480	6,490.467
	0.04	Rate of Withdrawal	mill.Ac.Ft.	194.5	0.0	0.0	9.0	8.0	3.0	2.0	22.0	93.0	0.0	0.0	4.0	12.0	4.0	4.0	24.0
		Expected Discounted Net Income	mill. dol.		231.522	216.329	521.363	432.334	166.626	108.555	1,676.729		253.645	574.061	1,090.766	1,037.486	270.110	525.260	3,751.328
	0.08	Rate of Withdrawal	mill.Ac.Ft.	194.5	0.0	0.0	9.0	8.0	3.0	2.0	22.0	91.0	0.0	0.0	4.0	12.0	5.0	4.0	25.0
		Expected Discounted Net Income	mill. dol.		131.816	123.166	299.084	247.473	94.868	62.030	958.437		144.438	541.535	1,028.963	1,057.053	151.302	495.499	3,418.790
		RLP Rate of Withdrawal	mill.Ac.Ft.	223.1	0.0	0.96	8.68	8.53	3.35	1.94	23.46	113.5	0.0	0.0	0.891	17.73	7.56	4.34	30.521

TABLE XXIX (Continued)

				Study Area	Model A							Study Area	Model B						
					Saturated Thickness in Ft.								Saturated Thickness in Ft.						
Stage	Discount at r =	Item	Unit	Level of Storage	0-100	101-200	201-300	301-400	401-500	>500	Total Study Area	Level of Storage	0-100	101-200	201-300	301-400	401-500	>500	Total Study Area
7 (2030-39)	0.00	Rate of Withdrawal	mill.Ac.Ft.	201.0	0.0	0.0	9.0	8.0	3.0	1.5	21.5	162.0	0.0	4.0	9.0	9.0	4.0	4.0	30.0
		Expected Discounted Net Income	mill. dol.		431.070	828.490	938.990	782.003	310.240	203.530	7,494.323		472.629	1,144.804	1,315.458	965.220	628.951	437.984	4,965.046
	0.04	Rate of Withdrawal	mill.Ac.Ft.	172.5	0.0	0.0	9.0	8.0	3.0	1.5	21.5	69.0	0.0	0.0	0.0	12.0	0.0	4.0	16.0
		Expected Discounted Net Income	mill. dol.		213.312	199.314	467.502	390.081	153.520	99.441	1,541.170		233.695	528.909	608.136	851.470	81.838	483.947	2,787.995
	0.08	Rate of Withdrawal	mill.Ac.Ft.	172.5	0.0	0.0	9.0	8.0	3.0	2.0	22.0	66.0	0.0	0.0	4.0	12.0	0.0	4.0	20.0
		Expected Discounted Net Income	mill. dol.		128.490	120.058	282.818	236.425	92.474	60.036	920.301		140.791	527.862	1,002.983	914.427	49.304	482.988	3,118.355
		RLP Rate of Withdrawal	mill.Ac.Ft.	199.6	0.0	0.08	8.59	8.69	3.78	2.41	23.55	83.0	0.0	0.0	0.006	6.63	7.30	4.26	18.196
8 (2040-49)	0.00	Rate of Withdrawal	mill.Ac.Ft.	179.5	0.0	0.0	9.0	8.0	3.0	1.5	21.5	132.0	0.0	4.0	4.0	9.0	7.0	4.0	28.0
		Expected Discounted Net Income	mill. dol.		323.300	604.760	690.420	581.413	229.280	151.970	2,581.143		354.197	825.154	880.309	697.502	498.861	310.094	3,566.117
	0.04	Rate of Withdrawal	mill.Ac.Ft.	151.0	0.0	0.0	9.0	8.0	3.0	2.0	22.0	53.0	0.0	0.0	0.0	4.0	0.0	4.0	8.0
		Expected Discounted Net Income	mill. dol.		186.358	174.128	399.000	336.568	132.159	87.034	1,315.247		204.165	462.077	531.293	592.260	71.497	399.121	2,260.413
	0.08	Rate of Withdrawal	mill.Ac.Ft.	150.5	0.0	0.0	9.0	8.0	3.0	2.0	22.0	46.0	0.0	0.0	0.0	4.0	0.0	4.0	8.0
		Expected Discounted Net Income	mill. dol.		121.308	113.348	260.302	219.884	86.028	56.278	857.148		132.917	498.342	572.990	638.743	46.545	430.446	2,319.983
		RLP Rate of Withdrawal	mill.Ac.Ft.	176.0	0.0	0.06	8.54	8.47	3.78	2.40	23.25	64.8	0.0	0.0	0.0	7.93	7.23	0.0	15.16

TABLE XXIX (Continued)

Stage	Discount at r =	Item	Unit	Study Area Level of Storage	Model A							Study Area Level of Storage	Model B						
					Saturated Thickness in Ft.								Saturated Thickness in Ft.						
					0-100	101-200	201-300	301-400	401-500	>500	Total Study Area		0-100	101-200	201-300	301-400	401-500	>500	Total Study Area
9 (2050-59)	0.00	Rate of Withdrawal	mill.Ac.Ft.	158.0	0.0	0.0	4.0	8.0	3.0	1.5	16.5	104.0	0.0	4.0	4.0	9.0	4.0	0.0	21.0
		Expected Discounted Net Income	mill. dol.		215.540	413.300	436.410	379.087	152.856	100.900	1,698.087		236.132	513.338	552.819	437.270	283.859	49.051	2,072.469
	0.04	Rate of Withdrawal	mill.Ac.Ft.	129.0	0.0	0.0	4.0	8.0	3.0	2.0	17.0	45.0	0.0	0.0	0.0	4.0	0.0	0.0	4.0
		Expected Discounted Net Income	mill. dol.		146.462	136.850	293.972	257.926	103.866	68.040	1,007.116		160.457	363.153	417.551	465.466	56.190	74.265	1,537.082
	0.08	Rate of Withdrawal	mill.Ac.Ft.	128.5	0.0	0.0	4.0	8.0	3.0	1.5	16.5	38.0	0.0	0.0	0.0	4.0	0.0	0.0	4.0
		Expected Discounted Net Income	mill. dol.		105.800	98.857	210.688	186.531	75.030	48.693	725.599		115.920	434.614	499.716	557.059	40.594	89.072	1,736.975
		RLP Rate of Withdrawal	mill.Ac.Ft.	152.7	0.0	0.0	7.04	8.27	3.78	2.46	21.55	49.6	0.0	0.0	0.0	4.03	7.25	4.48	15.76
10 (2060-69)	0.00	Rate of Withdrawal	mill.Ac.Ft.	141.5	0.0	- 0.0	0.0	8.0	3.0	1.5	12.5	83.0	0.0	3.0	4.0	9.0	0.0	0.0	16.0
		Expected Discounted Net Income	mill. dol.		107.770	184.620	115.760	188.298	75.540	50.63	722.618		118.866	208.546	227.382	249.210	41.345	24.526	869.075
	0.04	Rate of Withdrawal	mill.Ac.Ft.	112.0	0.0	0.0	0.0	8.0	3.0	2.0	13.0	37.0	0.0	0.0	0.0	4.0	0.0	0.0	4.0
		Expected Discounted Net Income	mill. dol.		87.409	81.672	93.887	152.725	61.271	40.366	517.330		95.761	216.730	249.195	277.791	33.534	44.418	917.429
	0.08	Rate of Withdrawal	mill.Ac.Ft.	112.0	0.0	0.0	0.0	8.0	3.0	2.0	13.0	34.0	0.0	0.0	0.0	4.0	0.0	0.0	4.0
		Expected Discounted Net Income	mill. dol.		72.312	67.567	77.672	126.348	50.689	33.394	427.982		79.223	297.030	341.522	380.713	27.743	60.875	1,187.106
		RLP Rate of Withdrawal	mill.Ac.Ft.	131.1	0.0	0.0	0.83	8.05	4.23	2.44	15.55	33.8	0.0	0.0	0.0	2.26	7.04	4.48	13.78

the interplay of these forces. Examining the optimal policies from stage to stage reveals that the optimal rates of ground water withdrawal are higher at the beginning of the planning horizon and progressively diminish towards the end.

In general solutions of the optimal rates of ground water withdrawal under the assumptions of Model A indicate that, except in a few borderline cases due to the discreteness of the states, the results are the same for the two discount rates of four and eight percent. The results for not discounting (i.e., for using a zero discount rate) indicate that the optimal rate of withdrawal is substantially reduced. This implies that the optimal policy is sensitive only to discount rates close to zero. If future returns are discounted at very low interest rates, the results show that it is advantageous to use a low rate of ground water withdrawal so that there will be an adequate supply for future years. Discounting at rates equal to or higher than four percent requires high rates of ground water withdrawal to maximize the present value of the net return stream for the ten stages of the planning horizon.

In Model B there is no difference between the optimal policies obtained by discounting at a rate of four percent and those obtained by using a rate of eight percent except in three stages. In stages one, six and seven discounting by eight percent results in higher rates of ground water withdrawal. The difference in the rates are two, one and four million acre feet in the respective stages. Note that the difference between the optimal rate of ground water withdrawal with no discounting and discounting by using either four or eight percent is substantially higher than that in Model A. This difference in stages one and two of Model B is about 36 million acre feet compared to 5.5 million acre feet in Model A, again reflecting the effect of the restrictive assumptions of product supply in Model I. As discounting at interest rates of four and eight percent encourage optimal policies of high rates of ground water withdrawal, the water in saturated-thickness class 0-100 feet becomes uneconomical for irrigation purposes, thus resulting in optimal policies of no water withdrawal in stage three. Diminishing net returns to water in saturated-thickness class 101-200 feet also cause optimal policies of reduced rates of ground water withdrawal in stage three. This means that the aggregate optimal policy for the study area is decreased to a lower rate of ground water withdrawal. Therefore, the gap in the aggregate optimal policy between discounting and not discounting diminishes in stages three and four. Beginning with stage five, the optimal rate of withdrawal in saturated-thickness class 101-200 feet with discounting becomes zero, narrowing the gap further. In stage six diminishing marginal net returns in saturated-thickness class 201-300 feet force a reduced optimal rate of withdrawal. Notice that the optimal rate of ground water withdrawal is higher with no discounting than with discounting. This illustrates that a slower rate of mining the aquifer over time is optimal when the time preference for money income is ignored. The slower withdrawal rate contributes to diminishing net returns of future years through increased pumping and distribution costs at a very gradual rate.

Policy Implications of the Results

It is interesting to compare the rate at which water is withdrawn from the aquifer by production Models I and II and the optimal policy suggested by the corresponding multi-stage sequential decision Models A and B. In order to make the comparison it may be necessary to reiterate the assumption that the results of the two linear programming models will be regarded as a close approximation of how irrigators will perform if decisions of allocating ground water are left for them to make on an individual basis. On the other hand, the solutions of the multi-stage sequential decision models are assumed to represent decisions on the intertemporal allocation of ground water being taken by all irrigators acting in concert through a public agency or through one or more water districts.

The last entries of each stage in Table XXIX give the corresponding linear programming rates of ground water withdrawal. Comparing the total rates of ground water withdrawal for the study area, Model I's rates are less than the rates suggested optimal by Model A in stages one, two and four for all three discount rates. In stages three and five they are somewhat higher than the optimal rate with no discounting, but less than the optimal rates with discount rates of four and eight percent. Model I's rates are slightly higher (1.3 to 5.6 million acre feet per stage) in stages six through ten. However, looking at the column in Table XXIX indicating the study area's level of ground water storage, one finds that Model I's storage levels are higher than those of Model A using four and eight percent discount rates. These results suggest that depleting the study area's water supply according to the solutions of Model I will not result in general uneconomic mining of the Central Ogallala Formation. The only control that can be justified economically may be well spacing to avoid the interference with neighboring wells.

A comparison of Model II's rate of ground water withdrawal with that suggested optimal by Model B shows that in stages one and two, Model II's rate is substantially lower (21 and 17 million acre feet, respectively) for discount rates using four and eight percent. In stage seven, the Model II rate of ground water withdrawal is about two million acre feet less than that of Model B for a discount rate of eight percent; but is about two million acre feet greater than that of Model B for a discount rate of four percent. As the difference is caused by the selection of alternative two instead of alternative one in saturated-thickness class 201-300 feet for a discount rate of eight percent in Model B, the irregularity in the solution may have been introduced by the discreteness of the data used. In the remaining stages, the rate of ground water withdrawal is greater in Model II than in Model B for both discount rates. The extent to which it is greater varies from two million acre feet in stages four and six to 11 million acre feet in stages eight and nine. However, looking at the study area level of ground water storage, Model II has a higher level of supply than those indicated for both discount rates in all stages except the last (see Table XXIX). A more accurate comparison of Model II and Model B solutions can be made by using the Model B aggregate conditional optimal rates of ground water withdrawal for 15 input states of the system shown in Table XXX. Let the system be in state one where the ground water storage is between 346 and 370 million acre feet and let the discount rate be four percent. Then, Table XXX indicates that the optimal policy to follow in stage one, where there are ten stages remaining in the planning horizon, is 68 million acre feet (6.8 million acre feet annually). If the system were in stage two the

TABLE XXX

AGGREGATE CONDITIONAL OPTIMAL POLICIES OF GROUND WATER WITHDRAWAL FOR POSSIBLE INPUT STATES OF THE SYSTEM ACCORDING TO MODEL B

State of the System	Ground Water Storage Level	Stage					Stage			
		1	2	3	4	5-10	1	2	3	4-10
		Stages Remaining in Planning Horizon					Stages Remaining in Planning Horizon			
		10	9	8	7	6-1	10	9	8	7-1
		r = 0.04					r = 0.08			
S_i	Mill. ac. ft.	Optimal Rates of Ground Water Withdrawal Mill. ac. ft.					Optimal Rates of Ground Water Withdrawal Mill. ac. ft.			
1	346-370	68	68	67	65	65	68	68	67	67
2	321-345	68	67	65	65	65	68	67	65	65
3	301-320	63	62	60	60	60	63	62	62	62
4	276-300	59	58	56	56	56	59	58	58	58
5	251-275	57	56	56	56	56	57	56	56	56
6	231-250	57	56	51	51	51	57	56	56	56
7	211-230	52	47	47	47	47	52	47	47	47
8	186-210	47	47	47	47	47	47	47	47	47
9	161-185	41	41	41	41	41	41	41	41	41
10	136-160	32	32	31	31	31	32	32	31	31
11	111-135	31	31	26	26	26	31	31	31	31
12	86-110	26	26	26	26	26	26	26	26	26
13	66-85	18	18	18	18	18	18	18	18	18
14	46-65	8	8	8	8	8	8	8	8	8
15	0-45	0	0	0	0	0	0	0	0	0

optimal policy would again be 68 million acre feet; but it would be 67 million acre feet if the system were in stage three. Notice that for stages four through ten, the optimal policy converges to a single value. For a discount rate of eight percent, convergence of the optimal policy occurs in stage three.

An examination of Table XXIX indicates that in stage two the RLP model shows a storage level of 311 million acre feet, which is state three, and Table XXX shows that the optimal withdrawal rate in stage two is 62 million acre feet for both four and eight percent discount rates, which shows that the Model II rate of withdrawal is 14 million acre feet less than that of Model B. In stage three, the RLP model shows a storage level of 263 million acre feet, which is state five, and Table XXX indicates that the optimal withdrawal rate is 56 million acre feet for discount rates of four and eight percent, which is two million acre feet less than the Model II rate of withdrawal indicated in Table XXIX. Similarly, it can be shown that the Model II rates of withdrawal are greater than that of Model B by one million acre feet in stage four, by 2.4 million acre feet in stage five, (for both discount rates respectively) by five million acre feet for a discount rate of four percent and by 0.1 million acre feet for a discount rate of eight percent in stage six, and by 0.2 million acre feet for both discount rates in stage seven. In stage eight the Model II solution uses 2.8 million acre feet less than that of Model B. In stages nine and ten the Model II rates of withdrawal are greater by 7.8 and 13.8 million acre feet, respectively.

The conclusion that can be drawn from the comparison of the results of Model II and Model B is that, if irrigation develops as suggested by

Model II, the rates of annual ground water withdrawal starting from stage three will exceed that which will maximize the study area's net returns over the remaining seven stages of the planning horizon. This implies that measures other than the spacing of wells may be necessary to regulate the extraction of ground water from the Central Ogallala Formation to conform to those rates which will maximize the study area's net returns over a longer period of time.

FOOTNOTES

[1] Ronald Howard, *Dynamic Programming and Markov Processes,* John Wiley and Sons, Inc., (New York, 1960), pp. 26-31.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The acreage of irrigated crop production in the semiarid region overlying the Central Ogallala Formation has been growing rapidly during the past decade. The annual natural recharge to the aquifer is insignificant relative to the quantity of water pumped annually. Thus the aquifer is being mined progressively from year to year. Irrigation is expected to expand in the area for some time to come which implies that the water supply is going to be depleted at a more rapid rate than currently observed. However, there are no available estimates of the changes that will take place in the growth of irrigation, depletion of the water supply and its repercussions on the pattern of crop production and income of the study area. The general purpose of this study is to estimate the magnitude of the changes that will take place with respect to these variables. The first part of this chapter presents a summary of the objectives of the study and the procedures employed in the course of the investigation to fulfill these objectives. The second part presents the highlights of the empirical results and draws some conclusions based on these results. Finally, the policy implications of the conclusions are discussed and the limitations of the study brought out. The need for further research in the study area is also stated.

Objectives and Procedures

The major objective of this study is to present estimates of (1) the growth of irrigation in the study area and (2) the rate of depletion of the aquifer over time and its effects on (a) the pattern of irrigated crop production and (b) the gross and net receipts to irrigated crop production over time. The study also investigates whether the projected rates of ground water depletion are optimal from the standpoint of maximizing the study area's net returns from irrigated crop production in the long run. More specifically, the first objective is to develop a model that (1) depicts the study area's irrigated crop production, (2) projects the growth in irrigation, (3) estimates the resulting rate of ground water withdrawal over time and (4) estimates the changes in gross and net returns to irrigated crop production over time. The second specific objective is to develop a multi-stage sequential decision model that determines the optimum rate of ground water withdrawal for a given planning horizon.

The study is composed of two separate but complementary analyses. The first part projects the future growth of irrigation under two assumptions and estimates the rate of ground water withdrawal from the Central Ogallala Formation, the pattern of irrigated crop production and the study area's income for each assumption. The implicit assumption used in this part of the study is that irrigators acting individually will use a short run approach of maximizing net returns to their water resource from one production period to the next. The second part of the study takes a long run approach of maximizing the present value of the stream of net returns accruing to the entire study area over a planning horizon of 100 years. The rates of ground water use resulting from the two approaches are compared and some policy implications inferred from the comparison.

The analysis in the study is based on an inventory of the soil and water resources taken from county soil surveys and various hydrologic studies of the Central Ogallala Formation. The study area was stratified into 48 discrete water resource situations based on saturated-thickness and depth-to-water classes. Irrigable soils of each water resource situation were grouped into four types. These soil and water resource situations formed the basis of the analysis. Two recursive linear programming models were employed to depict the pattern of irrigated crop production over the period 1965-2070. The distinction between the two models was made due to uncertainties about future development of irrigated production in the study area. The two models were designed to yield an estimate of the minimum and the maximum rate of irrigation development expected in the area.

Model I used the study area's historic share of the projected U. S. supply of the eight irrigated crops (grain sorghum, wheat, silage, corn, alfalfa, sugar beets, cotton and soybean) as a production goal. Hence, the Model I solution was forced to produce the study area's projected supply of the eight irrigated crops as long as the land and water resources permitted. In Model II an exponential growth equation was employed to project the maximum number of acres that could possibly be irrigated at different points in time taking into account the magnitude of the potentially irrigable land and the recent past trend in the growth of irrigation in the study area. Irrigation was allowed to grow to a maximum of this *a priori* projection. In addition, the area is required to produce a minimum of its historic share of the projected

U. S. supply of the eight irrigated crops as long as net returns from irrigation remain positive. All crops except cotton and sugar beets had no maximum production limits. The maximum production of cotton and sugar beets was limited to the study area's historic share of the projected national supply.

In the second part of the study a multi-stage sequential decision model was developed and the dynamic programming technique was used in order to determine the optimal allocation of ground water over a planning horizon of 100 years. The technique of parametric (or variable resource) programming was employed to generate the net returns that accrue to various alternative rates of ground water withdrawal at different storage levels of the aquifer. Two sets of net returns were generated from two sets of parametric programming models designed to incorporate the assumptions and results of Model I and Model II, respectively. The multi-stage sequential decision model was designed and run using the two sets of data. Model A refers to the sequential decision model using data reflecting the assumptions and results of Model I, while Model B is based on data reflecting the assumptions and results of Model II. The two multi-stage sequential decision models were designed as deterministic processes because annual natural recharge, the random variable affecting the state of the system, is negligible relative to the difference between successive states of ground water storage.

Findings and Conclusions

The two recursive linear programming production models were run for the period 1965-2070. The highlights of their results and conclusions are presented first. Presentation of the corresponding multi-stage decision models and their implications follows.

Results of Model I

The results of Model I indicate that the annual number of irrigated acres in the study area increases from 1.36 million in the 1965-69 period to a peak of 1.63 million in the 1990-99 period. The quantity of water pumped annually follows the same periodic trend. It increases from 2.4 million acre feet in the 1965-69 period to a peak of 3.03 million acre feet in the 1990-99 period. As mining of the ground water continues the stock reserve of water in the aquifer decreases steadily from an estimated 369.7 million acre feet in 1965 to a projected 124.9 million acre feet by 2070. The decrease in the ground water reserve is reflected by a decline in the water table from one production period to the next. The average decline in the water table in the 1965-69 period is 1.3 feet per year. It reaches a peak of 1.72 feet per year in the 1990-99 period and gradually declines to 0.97 feet per year in the 2060-69 period.

The consequence of the decline in the water table is reflected by reduced well capacities and increased pump lift, both of which increase the per unit cost of recovering water from the aquifer. *Ceteris paribus*, this implies a reduction in the net returns per acre of irrigated crops. The well capacity of resources in the first saturated-thickness class (0-100 feet) declines rapidly from 1965 to 1990, at which time irrigation on these resources is terminated. In resources of the second saturated-thickness class (101-200 feet) well capacity declines at a slower rate from 1965 to 2050, at which time irrigation is terminated in these resources. The area involved in the first and second saturated-thickness classes is about 1.8 and 1.7 million acres, respectively, which is 22.74 and 21.24 percent, respectively, of the total potentially irrigable land in the study area. In the rest of the four saturated-thickness classes, the rate of decline in well capacity is much slower and the results of Model I indicate that wells in those saturated-thickness classes have a physical life extending beyond 2070.

As Model I produces the study area's historic share of the projected national supply of the eight irrigated crops, irrigated acreages of each crop increase to a peak in the early periods and then decline to a low in the terminal period as production proceeds from 1965 to 2070, whereas the dryland acreages on grain sorghum, wheat, alfalfa and cotton progressively increase. The annual irrigated acreage of grain sorghum is projected to double that of 1965 by 2010. It increases from 0.52 million acres in 1965 to 1.09 million acres in 2060 and then declines to 0.54 million acres in the last production period 2060-69. The annual irrigated acreage of wheat increases from 0.74 million acres in 1965 to 0.84 million acres in the 1980-89 period. It fluctuates after 1990, but the trend is definitely downward. The annual irrigated acreage of corn increases from 36,236 in the 1965-69 period to a peak of 51,245 in the 1990-99 period. From then on it declines to a low of 31,949 in the terminal period despite some fluctuations between the period 2000-2020. The annual irrigated acreage of silage increases from 35,506 in the 1965-69 period to a peak of 55,911 in the 2020-29 period and then declines to a low of 27,788 acres in the final production period. Similarly the irrigated acreage of the remaining four crops reaches a peak before the year 2020 and then declines to a low in the terminal period 2060-69.

The annual aggregate gross receipts from irrigated production of crops increases from $116.1 million in the 1965-69 period to a peak of $145.2 million in the 2010-19 period, an increase of about 25 percent. After the year 2020 it gradually declines to a terminal low of $80.57 million in the 2060-69 period which is about 69 percent of the initial level. Despite the continued growth of annual aggregate gross returns from irrigation in the 1965-2020 periods, annual aggregate net returns from irrigation reaches its highest level of $48.2 million in the 1990-99 period, which is an increase of about 19 percent over the 1965-69 period level. After the year 2000 it declines steadily to its lowest level of $14.26 million in the terminal period, 2060-69, which is about 35 percent of the initial period. This clearly illustrates the effect of rising water costs as time progresses and mining of the ground water supply continues.

On the other hand, the annual aggregate gross returns from dryland crop production increases from $19.18 million in the 1965-69 period to a peak of $137.79 million in the 2050-59 period despite some fluctuations in the interim. The annual aggregate net returns from dryland crop production increases from $6.74 million in the initial period to a peak of $44.69 million in the 2020-29 period.

Results of Model II

The results of Model II indicate that the number of annual irrigated acres increases from 1.6 million in the initial period to a peak of 3.4 million in the 1990-99 period. After the year 2000 it declines precipitously to 0.89 million acres in the 2060-69 period. The *a priori* projected irrigated acreage is met as a maximum only in the first production period 1965-69. In the 1970-79 period, Model II's irrigated acreage is short of the projected maximum by 6,145 acres. This shortage increases progressively as the rapidly declining water table makes some of the water resource situations uneconomical for irrigated production. Irrigation terminates on the first three saturated-thickness classes (0-100 feet, 101-200 feet and 201-300 feet), respectively, by 1980, 2010 and 2040.

As Model II maximizes net returns subject to the conditions specified, irrigated acreage of each crop increases in the early periods and reaches a maximum in the 1990-99 production period. As the depletion of the ground water takes its adverse effect via increased water costs, the irrigated acreage of each crop declines to the minimum level in the terminal production period 2060-69. The dryland acreages of grain sorghum, wheat, alfalfa and cotton decline in the early periods when irrigation is expanding and then increase as some water resource situations are forced out of irrigated production due to rising water costs and unavailability of water.

The annual irrigated acreages and production of grain sorghum, wheat, corn and alfalfa grow to about 215 percent of their 1965 level by 1990. The annual irrigated acreages and production of silage, sugar beets, cotton and soybeans grow to 205, 156, 195 and 224 percent of the initial 1965 level, respectively, by 1990. In the terminal production period (2060-69), the annual irrigated acreage and production of grain sorghum drops to 48 percent of the initial level. It declines to 63 percent on wheat, to 75 percent on cotton, to 43 percent on silage and alfalfa, to 69 percent on sugar beets, to 35 percent on cotton, and to 50 percent on soybeans.

The aggregate annual gross receipts of the study area from irrigated production of crops increases from $136.6 million in the 1965-69 period to $291.7 million in the 1990-99 period, an increase of about 114 percent. During the same period of time aggregate annual net returns from irrigated production of crops increases from $49.7 million to $81.0 million, an increase of about 63 percent. This discrepancy between the growth rate of the aggregate gross and net returns arises from rising water costs as the water table declines. Aggregate annual gross receipts of the study area from irrigation decreases to its lowest level of $72.0 million in the 2060-69 period which is a substantial decrease of about $220.0 million, or 75 percent of the 1990-99 period. The decline in aggregate annual net returns from irrigation for the same period is projected to be about $70.3 million or 86.7 percent.

Comparison of the Results of Model I and Model II

The results of Model I and Model II exhibit similar trends over time. In both cases growth of irrigation in the study area occurs from 1965 to 2000. After the year 2000 the extent of irrigation in both models declines precipitously to its lowest level in the last production period 2060-69. In both cases irrigated production of crops and their aggregate gross and net receipts follow the trend in the growth and decline of irrigation. In both models the direction of changes in the level of underground water storage and well capacities is the same. The results differ only in magnitude and timing, which arise from differences in the basic assumptions of the two models. The assumptions incorporated in Model I result in a slower rate of irrigation development and hence a slower rate of depletion of the aquifer than Model II. Since no one can specify all of the information required by the models with certainty, one cannot indicate which model will approximate the actual occurrence of events in the future. Given the difference in assumptions for the two models, perhaps the most reasonable interpretation is that the results of Model I represent the minimum irrigation development that can be expected while the results of Model II represent the maximum. At any given time the real course of events may take place between these lower and upper estimates. Any interpretation of the future from the results of the two models will have to be conditioned and adjusted by what has been observed in the recent past.

Results of the Multi-Stage Sequential Decision Models

Solutions of the two multi-stage sequential decision models were obtained using three discount rates, zero, four and eight percent, to test the sensitivity of the solutions to changes in the discount rate. Solutions of the optimal rates of ground water withdrawal under the assumptions of Model A indicate that except in a few borderline cases due to the discreteness of the states, the results are the same for the two discount rates of four and eight percent. The solutions of Model B indicate that there is no difference between the optimal policies obtained by discounting at four percent and those obtained by discounting at eight percent except in three out of the ten stages. In stages one, six, and seven discounting by eight percent results in higher rates of ground water withdrawal. The differences in the rates of withdrawal are two, one and four million acre feet in the respective stages.

The results for a zero discount rate in both models A and B indicate that the optimal rate of withdrawal in each stage is substantially lower. This implies that the optimal policy is sensitive only to discount rates close to zero. If future returns are discounted at very low interest rates, the results show that it is advantageous to use a low rate of ground water withdrawal so that there will be an adequate supply of water for future years. Discounting at interest rates equal to or higher than four percent encourages higher rates of ground water withdrawal in order to maximize the present value of the net return streams from the entire planning horizon.

Policy Implications

It is recalled that the solutions of the two recursive linear programming models are regarded as a close approximation of the resulting intertemporal allocation of ground water in the Central Ogallala Formation if irrigators make individual decisions on a short run basis. On the other hand, the solutions of the multi-stage sequential decision models represent a situation in which decisions on the intertemporal allocation of ground water in the study area are made by all irrigators acting in concert through a public agency, or through one or more water districts. Since solutions of Model A and Model B maximize the total expected discounted net returns to the entire study area in the long run, they are considered to be optimal. Hence a comparison of the rate of ground water withdrawal obtained from Model I and Model II with those of Model A and Model B will serve as a yardstick whether irrigators acting individually will misallocate the ground water resource overtime.

A comparison of the solutions of Model I and Model A indicates that if the growth of irrigation in the study area progresses as projected by Model I, the rate of ground water withdrawal is less than that suggested optimal by Model A for discount rates other than zero. Since the relevant interest rate farmers face is closer either to four or eight percent than to zero one can conclude that if the water supply of the study area is depleted at the rate suggested by Model I, there are no indications of uneconomic mining of the Central Ogallala Formation. The policy implication is that restrictive measures on pumping ground water are not necessary. The only control measure that can be justified economically may be the spacing of wells so that interference between neighboring wells will be a minimum.

A comparison of Model II's rate of ground water withdrawal with that suggested optimal by Model B shows that in stages one and two, Model II's rates are substantially lower (21 and 17 million acre feet, respectively) for discount rates of four and eight percent. In the remaining eight stages, the rate of ground water withdrawal is greater in Model II than in Model B for both discount rates. One can conclude that if irrigation development occurs as projected by Model II, the population of the area should be concerned about uneconomic mining of ground water after 1990. The policy implication is that some control measures other than well spacing may be necessary to regulate the extraction of ground water from the Central Ogallala Formation to conform to those rates which will maximize the study area's net income over a longer period of time.

Limitations and Suggestions for Further Research

Mathematical representation of the real world is always subject to some degree of simplification and this study is no exception. Simplifying assumptions have been introduced in the formulation and specification of the models as well as in the application of relationships where accurate representations are not available. As the study incorporates both hydrologic and economic relationships it is useful to categorize its limitations accordingly.

Hydrologic Limitations

The hydrology of the area has not been exhaustively studied. While maps of saturated-thickness and depth-to-water are available from different sources, the important hydrologic parameters have been derived only for a few parts of the study area. The use of average parameters, such as the coefficient of storage, the coefficient of transmissibility and the rate of recharge for the entire study area, may introduce errors in the computations of the total volume of water available for pumping, the annual drawdown, well capacities and annual replenishment of the aquifer through recharge.

The assumption of a uniform decline of the water table throughout the study area may bias the economic life of water resource situations upwards where heavy pumpage occurs and downwards where pumpage is light.

The stratification of water resources by similar saturated-thickness class and depth-to-water class may introduce an artificial isolation to the extent that these resources are interspersed, which will bias the economic life of some resources upwards and that of others downwards.

These biases can be minimized only if more is known about the hydrology of the study area and a digital simulator of the entire aquifer is available.

Economic Limitations

The projections of growth in irrigation, the quantities of the various irrigated crops grown and the rate of depletion of the aquifer are affected by cost-price relationships, technological advances and the availability of capital and labor in the future. Consequently, this study is limited by the assumptions made with respect to these factors.

The input-output coefficients of Models I and II are held constant at the 1968 level throughout the 1965-2070 period. Technological advances in plant breeding may increase crop yields per acre which will, *ceteris paribus*, increase net returns in both models. Model I's projected number of irrigated acres is based on producing the study area's historic share of the projected national supply of the eight irrigated crops. Increased crop yields in the future will bias these projections upwards. Its effect on Model II is to bias the projection of crop production downward. Technological advances in the application and efficiency of irrigation water use may reduce the projected annual rate of ground water withdrawal and hence overstate both models' prediction of water use.

The assumed costs and prices may change in future years. If input costs increase and/or product prices decrease the projected economic life of the water resource situations will be over estimated. The converse will be true if input costs decrease and/or product prices increase in the future.

The models assume that the necessary labor and capital for the stated development will be available at the given prices. This may not be completely realistic. By and large the availability of capital and to some extent labor depends upon the general state of the economy. The equity position of the irrigator also plays an important role in determining whether he can expand his irrigation activities or not. The projected irrigation development in Model II could be upward biased if labor and capital become limited in the future at the assumed prices.

The models assume that maximizing net returns of the study area is the relevant objective. The results may be biased if in the future irrigators have other goals overriding their profit maximizing objective.

Furthermore, the assumptions that the study area will continue to produce the same crops may introduce biases in the projections if in the future the market for truck crops that could be grown in the study area develops. Though such a development seems unlikely at present, it cannot be ruled out completely. In Model I, the assumption that the study area will maintain its historic share of the national supply of the eight irrigated crops may bias the results if these shares do change in the future. The national supply of these crops was projected using the 1959-61 average production as a base. In Model I, the 1965-67 average production was used as a base in order to minimize such a bias.

The use of discrete time periods in the RLP models and discrete input-output states and discrete alternative rates of ground water withdrawal in the multi-stage sequential decision models, may have introduced some biases in the results. Refinements can be made by selecting smaller discrete intervals but at greater costs of time and funds required to process the input and output data.

Suggestions for Further Research

This study indicates that if future irrigation development follows the Model I projections uneconomic intertemporal allocation of ground water in the study area is unlikely. However, if irrigation development occurs at the rate projected by Model II, uneconomic mining of ground water from the Central Ogallala formation may occur after 1990. While these results do not define the exact extent of uneconomic ground water use, they do indicate that time is available for additional research before imposing control measures. Further research is necessary in both the hydrologic and economic aspects of the problem before specific control measures or no control measures are recommended for the area.

On the hydrologic side the development of a digital simulation model of the aquifer that is (1) capable of updating the hydrologic information that will be forthcoming as time proceeds and (2) capable of predicting future situations based on current hydrologic information and future economic projections will permit more accurate evaluation of alternative control measures. A more rigorous system of collecting annual ground water use from irrigators will help considerably in providing basic data for such an evaluation.

Research is also needed on improved methods of conveying ground water to the roots of crops with minimum loss in evaporation, seepage and tailwater. Using ground water more efficiently will prolong the economic life of the water resource. To the extent that the action of all irrigators is necessary to conserve irrigation water, the formation of irrigation associations or water districts should be encouraged throughout the study area.

On the economic side, further research is necessary in which representative farms are constructed to study specific problems of adjustment in the face of a declining water table. Decisions of additional investment in irrigation wells versus limiting irrigation to the available water supply are best done by the micro approach of studying a few farms. Additional research is necessary to study the effect of alternative methods of water use regulation on the regional supply of crops and farm income so that policy makers can evaluate the consequence of alternative decisions.

Finally, research is also needed to evaluate the secondary and tertiary benefits of irrigation to the study area. Such information will be crucial in the event interbasin transfer of water is feasible from surplus water areas.

Despite the limitations discussed above, the results of this study provide upper and lower estimates of the magnitude of the changes that will take place in the growth of irrigation, depletion of the ground water supply and its repercussions on the pattern of crop production and income of the study area. These estimates are useful for all members of the community (irrigators, land owners, businessmen, policy makers and researchers).

SELECTED BIBLIOGRAPHY

Barker, R., and R. F. Stanton. "Estimation and Aggregation of Firm Supply Functions", *Journal of Farm Economics*, Vol. 47, No. 3, August, 1965.

Beck, R. W., and Associates. *Ground Water Resources Study Relating to Portions of Prowers, Baca, and Las Animas Counties, Colorado*, February, 1967.

Bellman, Richard. *Dynamic Programming*, Princeton University Press, Princeton, New Jersey, 1957.

______. *Adoptive Control Processes: A Guided Tour*, Princeton University Press, Princeton, New Jersey, 1961.

Buchanan, J. W. *Geology and Ground Water Resources of the North Plains Ground-Water Conservation District No. 2*, Progress Report No. 2, 1967.

Cotner, M. L., John F. Fritschen, William H. Henebery and Joseph Biniek. *Soil and Water Use Trends in the Great Plains - Their Implications*, Great Plains Agricultural Council Publication No. 34, March, 1969.

Day, Richard H. "An Approach to Production Response", *Agricultural Economics Research*, Vol. 14, No. 4, October, 1962.

______. *Recursive Programming and Production Response*, North Holland Publishing Co., Amsterdam, 1963.

______. "On Aggregating Linear Programming Models of Production", *Journal of Farm Economics*, Vol. 45, No. 4, November, 1963, pp. 797-813.

Dietrich, Raymond A. *The Texas-Oklahoma Cattle Feeding Industry: Structure and Operational Characteristics*, Texas Agricultural Experiment Station, Texas A & M University, B-1079, December, 1968.

Fader, Stuart W., Edwin D. Gutentag, David H. Lobmeyer and Walter R. Meyer. *Geohydrology of Grant and Stanton Counties, Kansas*, Kansas State Geological Survey of Kansas Bulletin 168, University of Kansas, Lawrence, Kansas, 1964.

Henderson, James M. "The Utilization of Agricultural Land: A Theoretical and Emperical Inquiry", *Review of Economics and Statistics*, Vol. 41, No. 3, August, 1959, pp. 242-259.

Howard, Ronald. *Dynamic Programming and Markov Processes*, John Wiley and Sons, Inc., New York, 1960.

Kansas Water Resource Board. *A Hydrologic Ground Water Study*, Report No. 16(c), September, 1967.

Kaufman, A. "Graphs, Dynamic Programming, and Finite Games", *Mathematics in Science and Engineering*, Vol. 36, Academic Press, New York, 1961.

Nemhauser, George L. *Introduction to Dynamic Programming*, John Wiley and Sons, Inc., New York, 1966.

Pavelis, George A. "Irrigation Policy and Long-Term Growth Functions", *Agricultural Economics Research*, Vol. XVII, No. 2, April, 1965.

Sapick, D. B. and R. L. Goemaat. *Availability of Ground Water in Cimarron County, Oklahoma*, U. S. Geologic Survey, Unpublished Open File Atlas HA, Sheet 1, 1969.

Schoff, Stuart L. *Geology and Ground Water Resources of Texas County, Oklahoma*, Oklahoma Geological Survey, Bulletin No. 59, Norman, 1939.

Schaller, W. Neill. "A National Model of Agricultural Production Response", *Agricultural Economics Research*, Vol. 20, No. 2, April, 1968.

Shaffer, R. E., and V. R. Eidman. "The Cost Structure of Alternative Irrigation Distribution Systems", (Unpublished manuscript, Department of Agricultural Economics, Oklahoma State University).

Sharples, Jerry A. "The Representative Farm Approach to Estimation of Supply Response", *American Journal of Agricultural Economics*, Vol. 51, No. 2, May, 1969, pp. 353-361.

Stoe, George W., and O. A. Ljungstedt. *Geologic Map of the United States*, U. S. Geologic Survey 1932, Reprinted 1960.

Texas Agricultural Experiment Station, Texas A & M University, Panhandle Economic Program.

U. S. Department of Agriculture. *Preliminary Projections of Economic Activity in the Agricultural Forestry and Related Economic Sectors of the United States and Its Water Resource Regions 1980, 2000 and 2020*. For Use of the Water Resources Council and Cooperating Agencies for Comprehensive River Basin Planning. Prepared by Economic Research and Forest Service, August, 1967.

U. S. Geologic Survey, Water Resource Division. *Ground Water in the Cimarron River Basin*, Prepared for the U.S. Corps of Engineers, Tulsa District, 1966.

Vollmar, Glen J. *Irrigated Agriculture - Potential for the Great Plains*, Great Plains Agricultural Council Publication No. 34, March, 1969.

Water Resources Council. *Interim Price Standards for Planning and Evaluating Water and Land Resources*, April, 1966, Washington, D.C.

APPENDIX A

DEFINITION OF TERMS

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Aquifer: A water-bearing reservoir rock, such as a particular formation or a stratum.

Coefficient of Storage: The volume of water released from storage in each vertical column of the aquifer having a base of one foot square when the water table declines one foot. This is equal to the specific yield for non-artesian aquifers.

Coefficient of Transmissibility: The rate of flow of water in gallons per day, at the prevailing water temperature, through each vertical strip of the aquifer one foot wide having a height to the thickness of the aquifer and under a unit hydraulic gradient.

Various references have been made in the text to geologic periods, e.g., Cretaceous, Permian, etc., when systems of rocks were deposited. The following geologic time chart gives the geologic systems and their approximate time in the evolution of the earth.

TABLE XXXI

GEOLOGIC TIME CHART

System And Period	Series And Epoch	Distinctive Records of Life	1,000 Years
	CENOZOIC ERA		
Quaternary	*Recent*	Modern Man	II
	Pleistocene	Early Man	1,000
Tertiary	*Pliocene*	Large carnivores	
	Miocene	Whales, apes, grazing forms	
	Oligocene	Large browsing mammals	
	Eocene	Rise of flowering plants	
	Paleocene	First Placental mammals	70,000
	MESOZOIC ERA		
Cretaceous		Extinction of dinosaurs	130,000
Jurassic		Dinosaurs' zenith, primitive birds, first small mammals	160,000
Triassic		Appearance of dinosaurs	200.000
	PALEOZOIC ERA		
Permian		Reptiles developed, conifers abundant	235,000
Carboniferous			
Upper (Pennsylvanian)		First Reptiles,coal forests	260,000
Lower (Mississippian)		Sharks abundant	285,000
Devonian		Amphibians appeared, fishes abundant	320,000
Silurian		Earliest land plants and animals	350,000
Ordovician		First primitive fishes	400,000
Cambrian		Marine invertebrates	500,000
	PRE-CAMBRIAN TIME		
		Few fossils	3,500,000-4,000,000

Source: Encyclopaedia Britannica. Chicago, 1967, vol. 5, p. 728.

APPENDIX B

STUDY AREA MEAN MONTHLY PRECIPITATION

TABLE XXXII

STUDY AREA MEAN MONTHLY PRECIPITATION 1941-1965

	Counties in				Study Area
Month	Colorado	Kansas	Oklahoma	Texas	Weighted Mean[1]
Jan	0.39	0.45	0.46	0.40	0.42
Feb	0.35	0.53	0.65	0.48	0.53
Mar	0.91	0.97	1.00	0.82	0.91
Apr	1.34	1.68	1.47	1.30	1.45
May	2.56	3.24	2.92	2.86	2.95
Jun	2.40	3.03	2.80	2.48	2.71
Jul	2.49	3.20	3.15	3.50	3.26
Aug	2.11	2.60	2.63	2.49	2.54
Sep	1.15	1.51	1.52	1.56	1.51
Oct	0.90	1.52	1.29	1.57	1.44
Nov	0.57	0.67	0.74	0.55	0.63
Dec	0.36	0.44	0.57	0.48	0.48
TOTAL	15.53	19.84	19.20	18.49	18.83

Source: U. S. Department of Commerce, Weather Bureau, Climatological Data: Colorado, Kansas, Oklahoma, Texas (Ashville, 1941-1965).

[1] The weights used are the ratios of each state's acreage included in the study area to the total number of acres in the study area; 0.06 in Colorado, 0.27 in Kansas, 0.27 in Oklahoma and 0.40 in Texas.

APPENDIX C

PRODUCTION OF THE EIGHT PRINICIPAL IRRIGATED CROPS IN THE STUDY AREA

TABLE XXXIII

PRODUCTION OF THE EIGHT PRINCIPAL IRRIGATED CROPS IN THE STUDY AREA, 1964[1]

	Sorghum		Wheat		Corn Grain		Silage[b]		Alfalfa		Sugar Beets		Cotton		Soy Beans		Total
	Acres	Bu.	Acres	Bu.	Acres	Bu.	Acres	Tons	Acres	Tons	Acres	Tons	Acres	Bales	Acres	Bu.	Acres
Colorado																	
Irrigated	5,996	298,947	5,066	166,677	370	21,047	916	11,842	2,915	7,888	1,251	18,281	-	-	-	-	16,514
Dryland	20,641	211,570	64,405	740,658	71	2,624	314	668	688	1,409	-	-	-	-	-	-	86,119
Kansas																	
Irrigated	112,055	7,100,925	113,582	3,651,770	17,605	1,357,019	8,864	134,429	4,268	18,405	6,304	97,109	-	-	-	-	262,678
Dryland	241,563	2,777,975	468,989	5,930,970	1,997	90,839	4,473	9,527	3,539	8,528	-	-	-	-	-	-	720,561
Oklahoma																	
Irrigated	19,603	1,242,330	30,724	911,724	-	-	-	-	1,320	4,400	-	-	-	-	77	1,893	51,724
Dryland	142,469	1,638,394	363,860	3,661,395	16	314	8,998	19,166	2,153	5,123	-	-	-	-	-	-	517,496
Texas																	
Irrigated	195,385	12,185,648	161,233	5,357,939	175	18,184	6,051	94,162	2,575	9,014	-	-	1,443	1,448	1,148	28,222	368,101
Dryland	77,201	887,812	375,856	4,223,920	27	675	1,097	2,337	438	859	-	-	98	82	-	-	454,717
Study Area																	
Irrigated	333,039	20,827,850	310,605	10,088,110	18,150	1,396,250	15,831	240,433	11,078	39,707	7,555	115,392	1,443	1,448	1,225	30,115	698,926
As % of Total Irrigated Acres	47.65		44.44		2.60		2.26		1,58		1.08		0.21		0.18		
Dryland	481,874	5,515,751	1,273,110	14,556,943	2,111	94,452	14,882	31,698	6,818	15,919	-	-	98	82	-	-	1,778,893
As % of Total Irrigated Acres	27.09		71.56		0.12		0.84		0.38		--		0.01		--		

Source: United States Department of Commerce, Bureau of the Census, 1964 Census of Agriculture, Volume I, Parts 21, 36, 37 and 41, U. S. Government Printing Office, 1967.

[a] Includes only acreages that have been fully irrigated.

[b] Includes both corn and sorghum silages.

APPENDIX D

WATER RESOURCES

APPENDIX D

WATER RESOURCES

The Ogallala Formation as a Hydrologic Unit

Technically the name "Ogallala Formation" refers to sediments deposited in the *Pliocene* series of the *Tertiary* age. However, since deposits in the *Pleistocene* series of the *Quaternary* age have similar hydrologic properties to those of the *Pliocene* series, various hydrologists including Marine and Schoff have regarded the two deposits as a single hydrologic unit and referred to it as the Ogallala Formation.[1] However, in the northwestern part of the study area the Pliocene and Pleistocene deposits are underlain by rocks of earlier formations that yield water to multiple screened wells. Hydrologic studies of the counties, Baca and Prowers (Colorado),[2] Grant and Stanton (Kansas),[3] and Cimarron (Oklahoma)[4] show that the *Cheyenne Sandstone*, the *Kiowa Shale* and the *Dakota Sandstone*, all of which are rocks formed in the lower series of the *Cretaceous* age, are present beneath the Ogallala Formation. In some areas all three formations underlie the Ogallala while in others only one or two of them may do so. To a small extent the *Dockum Group* formation is also present in Grant and Stanton Counties, Kansas. The study for the Corps of Engineers shows the Dakota and Cheyenne Sandstones are present in small parts of Grant, Morton, Haskell, Stevens and Seward Counties in Kansas.[5] In all other parts of the study area the Ogallala deposits of the Tertiary and Quanternary ages lies directly above the non-water yielding red beds of the Perian age. While the Ogallala deposits underlie 100 percent of the study area, the other formations intrude in less than 20 percent of the area. Due to this overwhelming dominance in occurence and the superior water-yielding property of the Pliocene and Pleistocene deposits, the term "Ogallala" seems to be used in a broad content when referring to the aquifer of the entire area. Figure 4 is a sample geologic cross section showing the various relative positions of the different formations in areas where they may occur together. The physical and water-bearing characteristics of each formation and the range of their *saturated-thickness* is summarized in Table XXXIV

The Hydrologic Properties of the Aquifer

The quantity of ground water available for pumping is determined by the hydrologic properties of the aquifer. The depth of the water-saturated material (*saturated-thickness*), its *coefficient of storage* and the corresponding surface area associated with it determine the absolute amount of water available for pumping. The saturated-thickness of the aquifer in the study area ranges from a few feet along the river beds to over 500 feet as in Stevens and Seward Counties (Kansas), Beaver and Texas Counties (Oklahoma) and Ochiltree County (Texas). The saturated-thickness of the aquifer in Baca and Prowers Counties (Colorado) is less than 200 feet. About 90 percent of the entire surface area has a saturated-thickness of less than 400 feet.

The coefficient of storage, which under water table conditions is equal to the specific yield is estimated to be about 0.15. This implies that the volume of water the aquifer releases by gravity is only

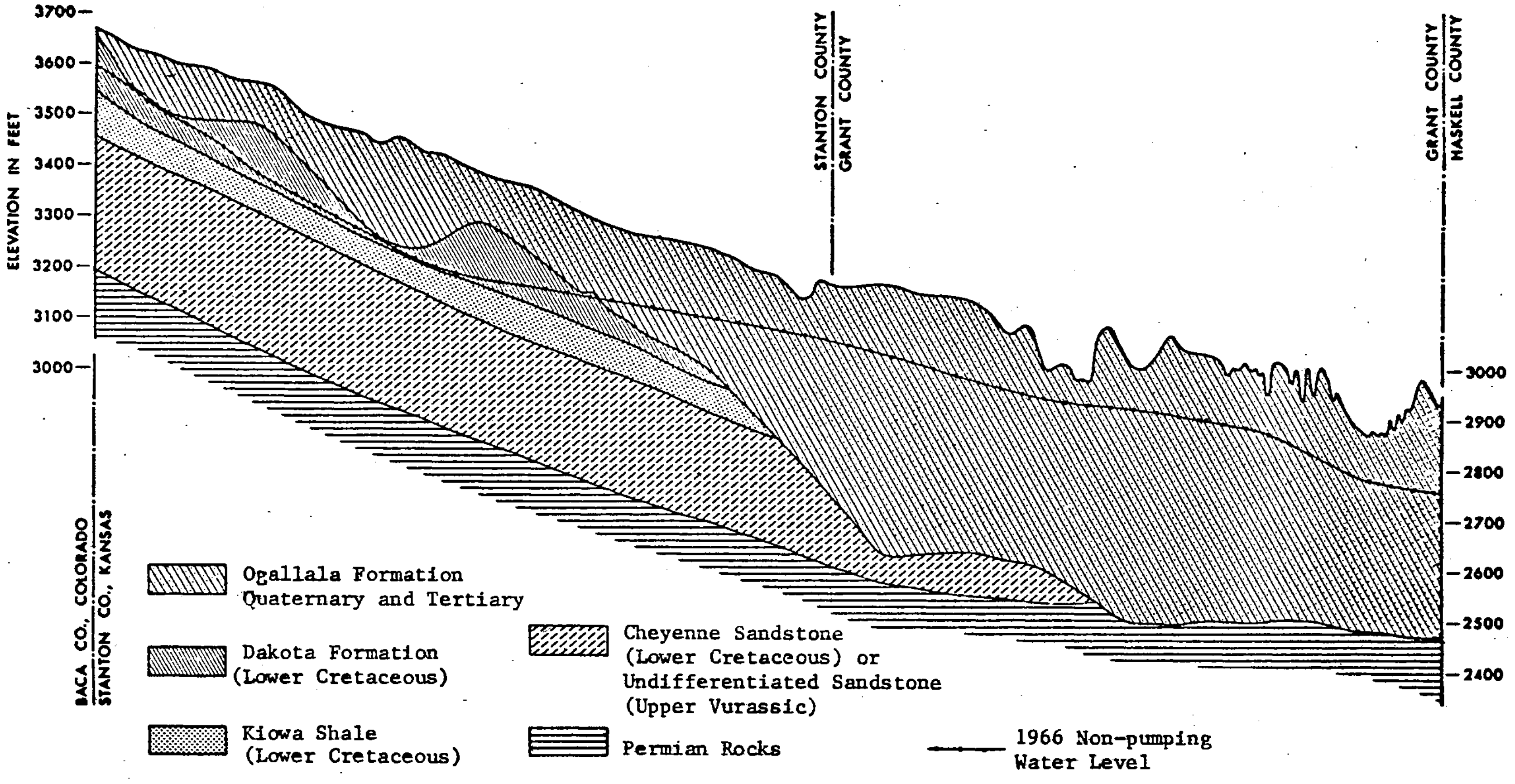

Figure 5. Geologic Cross-Section: Multiple Aquifers

Source: Kansas Water Resource Board, A Hydrologic Ground-Water Study (Report No. 16(c)), September, 1967, Figure 9.

TABLE XXXIV

GEOLOGIC FORMATIONS AND THEIR WATER BEARING PROPERTIES

System	Series	Stratigraphic Unit (formation)	Thickness in ft.	Physical Characteristics	Water Bearing Characteristics
Quaternary	Pleistocene	Ogallala	0 to 500±	Clay, silt, very fine to coarse sand, gravel, clay, caliche and algal limestone.	Yields moderate to a large quantity of water. Wells yield up to over 1000 gpm.
Tertiary	Pliocene				
Cretaceous	Lower	Dakota Sandstone	0 to 135±	Fine to medium grained sandstone with shale beds.	Yields small supply of water to stock and domestic wells. Yields water to multiple acquifer irrigation wells.
		Kiowa Shale	0 to 150±	Gray to black platy, calcareous clayey shale.	Yields little or no water.
		Cheyenne Sandstone	0 to 120±	Massive white to buff fine-grained sandstone	Yields small to moderate quantities of water. Wells yield up to 500 gpm.
Triassic	Upper	Dockum Group	0 to 130±	Red silt stone, shale, limestone, fine to coarse sandstone.	Yields small supply of water to stock and domestic wells. Yields water to multiple acquifer irrigation wells.
Permian	Upper	Big Basin (Red bed)	160±	Dark red mud stone.	Yields no water chemically suitable for irrigation.

Source: Adopted from Fader, Stuart, et. al., "Geohydrology of Grant and Stanton Counties, Kansas," (State Geological Survey of Kansas, Bulletin 168, the University of Kansas, Lawrence, Kansas, 1965), p. 13, and Beck, R. W., and Associates, "Ground Water Resource Study Relating to Portions of Prowers, Baca and Las Animas Counties, Colorado," February, 1967, pp. 12-13.

15 percent of the volume of the saturated material. The rate at which water is released to wells is determined by the coefficient of transmissibility of the aquifer. This coefficient varies throughout the study area depending on the depth of the saturated-thickness. It ranges from approximately 25,000 gallons per day per foot (g.p.d./ft.) in areas of shallow saturated-thickness to 590,000 g.p.d./ft. The aquifer yields an average of 1,000 g.p.m. to eight-inch wells in areas where the saturated-thickness is sufficiently deep (100 feet or more) to sustain an adequate flow of water into the well.[6]

The depth from the surface to the water level in the aquifer is one important parameter in determining the cost of pumping water. The depth-to-water in the Colorado and Kansas portion of the study area is less than 200 feet. It increases as much as 300 feet in Cimarron and Texas Counties in Oklahoma. In the Texas portion of the study area the depth-to-water is 400 feet in portions of all counties except Moore and Sherman where it is less than 300 feet deep. In 1964, about 80 percent of the entire aquifer had a depth-to-water of less than 200 feet. The total volume of water theoretically available for pumping from the Central Ogallala Formation was estimated to be about 370 million acre feet in 1965.

Chemical Quality of the Water in Storage

Water in the Pliocene and Pleistocene deposits is of uniformly good quality throughout the plains. It is rated good to excellent for irrigation. It contains between 200-500 parts per million (p.p.m.) of disolved solids and has commonly a hardness of 150-300 p.p.m. The water is commonly used for municipal supplies without treatment for hardness. Buchanan reports that generally it meets the standards set forth by the United States Health Department for domestic use. Water in the deposits beneath the Ogallala are generally more mineralized. The water is commonly treated for municipal supplies, but it is generally satisfactory for irrigation.[7]

Recharge

The three principal sources of recharge to an aquifer are (1) underflows from adjacent aquifers, (2) underflows from streams and (3) percolation from rainfall and irrigation.

The Central Ogallala Basin has been dissected to the Permian bed rock by the Arkansas River to the north and the South Canadian River to the south. Therefore, there are no underflows from the formations to the north and the south. The gradient of the formation is in an easterly direction throughout the aquifer, a phenomenon that rules out underflows from adjacent aquifers to the east. In the southern part of Baca County, Colorado, and the western part of Cimarron County, Oklahoma, the Cheyenne and Dakota Sandstones are pinched out and their discharge, though not significant, flows into the Central Ogallala Basin. In other areas in the west, the Ogallala has been eroded and crops out and no significant underflows from other aquifers are possible. The Arkansas, the Cimarron, the North and South Canadian Rivers are the principal streams that bring surface water into the study area. However, the Ogallala is either very thin or nonexistent along the stream beds and recharge from stream flows is negligible. Consequently, the only significant recharge to the aquifer is derived from precipitation and in areas where irrigation is extensively developed from percolation of irrigation water. As the study area is a region of scant rainfall, and high evapotranspiration (as noted earlier), only a small amount of the water received on the surface percolates to replenish the underground water reserve. The mean recharge of the Central Ogallala Formation is estimated to be about 0.3 inches per year.[8] Multiplying the amount of surface area in the Central Basin of the Ogallala by this coefficient results in an estimate of total annual recharge of about 270,000 acre feet.

Discharge

Discharge from the aquifer takes the form of (1) pumpage from wells, (2) leakage into streams and (3) subsurface flow into adjacent aquifers. Since much of the water table has fallen below the elevation of stream beds and much of the Ogallala in the western part is erodded and crops out to the surface, very little water is discharged to streams and other aquifers. The rate of discharge is primarily a function of the quantity of water pumped out for irrigation, municipal and industrial purposes.[9]

Irrigation is by far the largest user of ground water. In 1965, an estimated 2.32 million acre feet of water was pumped for irrigation in the study area. The total volume used for municipal and industrial purposes in the same period was an estimated 104,168 acre feet.

FOOTNOTES

[1] Wendell I. Marine and Stuart L. Schoff, Ground Water, Beaver County, Oklahoma Geologic Survey, Bulletin 97 (1962), p. 25.

[2] Beck, et.al., pp. 17-21.

[3] Stuart W. Fader, et.al., Geohydrology of Grant and Stanton Counties, Kansas, State Geological Survey of Kansas, Bulletin 168, University of Kansas, Lawrence (1964), pp. 14-32.

[4] Sapick, pp. 17-21.

[5] U. S. Geologic Survey, Water Resource Division, Ground Water in the Cimarron River Basin, prepared for the U. S. Corps of Engineers, Tulsa District (1966), p. 35.

[6] Fader, et.al., p. 32, Buchanan, p. 16, Beck, et.al., p. 23, p. 28, and personal interview with Mr. David B. Sapick, Chief, U. S. Geologic Survey Team at Guymon, Oklahoma, September, 1967.

[7] Beck, et.al., p. 17, Buchanan, p. 16, and James H. Irwin and Robert B. Morton, Hydrogeologic Information on the Glorieta Sandstone and the Ogallala Formation in the Oklahoma Panhandle and Adjoining Areas as Related to Underground Waste Disposal, U. S. Geologic Survey, Geological Survey Circular 630 (Washington, 1969), p. 11.

[8] Beck, et.al., p. 27, Buchanan, p. 9, Marine and Schoff, p. 28, and U. S. Geologic Survey, p. 46.

[9] Beck, et.al., p. 30 and Buchanan, p. 9.

APPENDIX E

ENTERPRISE BUDGETS

APPENDIX E

ENTERPRISE BUDGETS

The enterprise budgets used in the two polyperiod recursive linear programming production models were developed from several sources. The basic data for all crops except sugar beets and cotton were taken from the enterprise budgets developed for the Oklahoma Panhandle by Green, et. al., and updated in consultation with the area agronomist and farm management specialist.[1] The data for cotton was adopted from studies in the High Plains of Texas and southwestern Oklahoma.[2] The data for sugar beets were taken from studies in Colorado and Kansas.[3] Tables XXXV and XLII present the crop enterprise budgets. Table XLIII shows the schedule of irrigation and amount of water application for each crop. A breakdown for sugar beets was not available.

TABLE XXXV

GRAIN SORGHUM: PRODUCTION COSTS AND RETURNS PER ACRE ON DRYLAND AND IRRIGATED CLAY LOAM AND SANDY LOAM EXCLUDING THE COST OF WATER

Item	Unit	Dryland			Inches of Irrigation Water					
						16"			24"	
		Price or Cost Per Unit	Quantity	Value or Cost	Price or Cost Per Unit	Quantity	Value or Cost	Price or Cost Per Unit	Quantity	Value or Cost
				Clay Loam Soils						
Production										
Grain	Cwt.	1.65	9.05	14.93	1.65	45.00	74.25	1.65	62.00	102.30
Pasture	Aum.	-	0.20	-	-	1.00	-	-	1.40	-
Gross Return	Dol.	-	-	14.93	-	-	74.25	-	-	102.30
Inputs										
Seed	Bu.	0.22	4.00	0.88	0.22	10.00	2.20	0.22	10.00	2.20
Fertilizer N Pre Plant +										
Side Dress	Lb.	-	-	-	0.045	85.00	3.82	0.045	125.00	5.62
N in Water	Lb.	0.07	20.00	1.40	0.10	17.00	1.70	0.10	25.00	2.50
Crop Insurance	$100	6.00	0.14	0.84	6.00	0.60	3.60	6.00	0.80	4.80
Power & Machinery (oper.)	Hr.	1.14	2.76	3.15	1.14	4.01	4.57	1.14	4.01	4.57
Power & Machinery (Fixed)	Hr.	1.03	2.76	2.84	1.03	4.01	4.13	1.03	4.01	4.13
Herbicide	Acre	-	-	-	4.50	1.00	4.50	4.50	1.00	4.50
Insecticide	Acre	-	-	-	2.00	1.00	2.00	2.00	1.00	2.00
Harvesting and Hauling	Cwt.	0.20	9.05	1.81	0.20	45.00	9.00	0.20	62.00	12.40
Interest Annual Capital	Dol.	0.07	2.63	0.18	0.07	10.67	0.75	0.07	11.19	0.78
Labor	Hr.	1.50	1.51	2.26	1.50	2.28	3.42	1.50	2.28	3.42
Total Specified Costs	Dol.			13.36			39.69			46.92
				Sandy Loam Soils						
Production										
Grain	Cwt.	1.65	13.70	22.60	1.65	42.00	69.30	1.65	59.00	97.35
Gross Return	Dol.	-	-	22.60	-	-	69.30	-	-	97.35
Inputs										
Seed	Lb.	0.22	4.00	0.88	0.22	10.00	2.20	0.22	10.00	2.20
Fertilizer N Pre Plant +										
Side Dress	Lb.	0.07	20.00	1.40	0.035	85.00	2.98	0.035	125.00	4.38
N in Water	Lb.	-	-	-	0.10	17.00	1.70	0.10	25.00	2.50
Crop Insurance	$100	6.00	0.20	1.20	6.00	0.56	3.36	6.00	0.95	5.70
Power & Machinery (oper.)	Hr.	1.14	2.76	3.15	1.14	4.01	4.57	1.14	4.01	4.57
Power & Machinery (Fixed)	Hr.	1.03	2.76	2.84	1.03	4.01	4.13	1.03	4.01	4.13
Herbicide	Acre	-	-	-	4.50	1.00	4.50	4.50	1.00	4.50
Insecticide	Acre	-	-	-	2.00	1.00	2.00	2.00	1.00	2.00
Harvesting and Hauling	Cwt.	0.20	13.70	2.74	0.20	42.00	8.40	0.20	59.00	11.80
Interest Annual Capital	Dol.	0.07	3.00	0.21	0.07	10.54	0.74	0.07	11.01	0.77
Labor	Hr.	1.50	1.51	2.26	1.50	2.28	3.42	1.50	2.28	3.42
Total Specified Costs	Dol.			14.68			38.00			45.97

TABLE XXXVI

WHEAT: PRODUCTION COSTS AND RETURNS PER ACRE ON IRRIGATED CLAY LOAM AND SANDY LOAM SOILS EXCLUDING WATER COSTS

		Dryland			Inches of Irrigation Water					
						8"			18"	
Item	Unit	Price or Cost Per Unit	Quantity	Value or Cost	Price or Cost Per Unit	Quantity	Value or Cost	Price or Cost Per Unit	Quantity	Value or Cost
				Clay Loam Soils						
Production										
Grain	Bu.	1.29	13.80	17.80	1.29	30.00	38.70	1.29	45.00	58.05
Pasture	AUM	8.00	0.25	2.00	8.00	0.30	2.40	8.00	1.00	8.00
Gross Returns	Dol.	-	-	19.80	-	-	41.10	-	-	66.05
Inputs										
Seed	Bu.	2.25	0.50	1.12	2.25	1.00	2.25	2.25	1.00	2.25
Fertilizer N	Lb.	0.07	10.00	0.70	0.07	40.00	2.80	0.07	80.00	5.60
P	Lb.	-	-	-	-	-	-	0.08	80.00	6.40
Crop Insurance	$100	6.00	0.17	1.02	6.00	0.46	2.76	6.00	0.50	3.00
Power & Machinery (Oper.)	Hr.	1.27	1.68	2.13	1.27	2.68	3.40	1.27	2.83	3.59
Power & Machinery (Fixed)	Hr.	1.04	1.68	1.74	1.04	2.68	2.79	1.04	2.83	2.94
Harvesting	Ac.	3.50	1.00	3.50	4.00	1.00	4.00	4.00	1.00	4.75
Hauling	Bu.	0.08	13.80	1.10	0.08	30.00	2.40	0.08	45.00	3.60
Interest Annual Capital	Dol.	0.07	4.28	0.28	0.07	10.51	0.74	0.07	15.06	1.05
Labor	Hr.	1.50	1.01	1.51	1.50	1.56	2.34	1.50	1.73	2.60
Total Specified Costs	Dol.			13.10			23.48			35.78
				Sandy Loam Soils						
Production										
Grain	Bu.	1.29	9.40	12.13	1.29	30.00	38.70	1.29	50.00	64.50
Pasture	AUM	8.00	0.25	2.00	8.00	0.50	4.00	8.00	1.00	8.00
Gross Returns	Dol.			14.13			42.70			72.50
Inputs										
Seed	Bu.	2.25	0.50	1.12	2.25	1.00	2.25	2.25	1.00	2.25
Fertilizer N	Lb.	0.05	15.00	1.75	0.05	60.00	3.00	0.05	100.00	5.00
P_2O_5	Lb.	-	-	-	0.08	20.00	1.60	0.08	40.00	3.20
Crop Insurance	$100	6.00	0.12	0.72	6.00	0.38	2.28	6.00	0.625	3.75
Power & Machinery (Oper.)	Hr.	1.27	1.68	2.13	1.27	2.83	3.59	1.27	2.83	3.59
Power & Machinery (Fixed)	Hr.	1.04	1.68	1.74	1.04	2.68	2.79	1.04	2.83	2.94
Harvesting	Ac.	3.50	1.00	3.50	4.00	1.00	4.00	5.00	1.00	5.00
Hauling	Bu.	0.08	9.40	0.75	0.08	30.00	2.40	0.08	50.00	4.00
Interest Annual Capital	Dol.	0.07	4.36	0.31	0.07	11.48	0.80	0.07	17.84	1.25
Labor	Hr.	1.50	1.01	1.51	1.50	1.56	2.34	1.50	1.73	2.60
Total Specified Costs	Dol.			13.53			25.05			33.58

TABLE XXXVII

CORN GRAIN: PRODUCTION COSTS AND RETURNS PER ACRE ON IRRIGATED CLAY LOAM AND SANDY LOAM SOILS EXCLUDING WATER COSTS

Item	Unit	Inches of Irrigation Water					
		Price or Cost Per Unit	20"		Price or Cost Per Unit	24"	
			Quantity	Value or Cost		Quantity	Value or Cost
Production							
Grain	Bu.	1.12	100.00	112.00	1.12	130.00	145.60
Gross Return	Dol.	-	-	112.00	-	-	145.60
Inputs							
Seed	Lb.	0.30	20.00	6.00	0.30	20.00	6.00
Fertilizer N pre Plant + Side Dress	Lb.	0.035	150.00	5.25	0.035	150.00	5.25
N in Water	Lb.	0.10	50.00	5.00	0.10	50.00	5.00
P_2O_5	Lb.	0.08	40.00	3.20	0.08	40.00	3.20
Crop Insurance	$100	11.00	0.60	6.60	11.00	0.80	8.80
Power & Machinery (Oper.)	Hr.	1.14	4.01	4.57	1.14	4.01	4.57
Power & Machinery (Fixed)	Hr.	1.03	4.01	4.13	1.03	4.01	4.13
Herbicide	Acre	4.50	1.00	4.50	4.50	1.00	4.50
Insecticide	Acre	3.50	1.00	3.50	3.50	1.00	3.50
Harvesting & Hauling	Bu.	0.20	100.00	20.00	0.20	130.00	26.00
Interest Annual Capital	Dol.	0.07	16.15	1.13	0.07	17.41	1.22
Labor	Hr.	1.50	1.90	2.85	1.50	2.28	3.42
Total Specified Costs	Dol.			66.73			75.59

TABLE XXXVIII

CORN SILAGE: PRODUCTION COSTS AND RETURNS PER ACRE ON IRRIGATED CLAY LOAM AND SANDY LOAM SOILS EXCLUDING WATER COSTS

			Inches of Irrigated Water				
			10"			24"	
Item	Unit	Price or Cost Per Unit	Quantity	Value or Cost	Price or Cost Per Unit	Quantity	Value or Cost
			Clay Loam Soils				
Production							
Grain	Bu.	5.50	12.00	66.00	5.50	20.00	110.00
Gross Return	Dol.	-	-	66.00	-	-	110.00
Inputs							
Seed	Lb.	0.25	20.00	5.00	0.25	20.00	5.00
Fertilizer N Pre Plant +							
Side Dress	Lb.	0.045	80.00	3.60	0.045	150.00	6.75
N in Water	Lb.	0.10	30.00	3.00	0.10	50.00	5.00
P_2O_5	Lb.	0.08	20.00	1.60	0.08	40.00	3.20
Crop Insurance	$100	11.00	0.48	5.28	11.00	0.80	8.80
Power & Machinery (Oper.)	Hr.	1.11	3.66	4.06	1.11	3.66	4.06
Power & Machinery (Fixed)	Hr.	0.99	3.66	3.62	0.99	3.66	3.62
Herbicide	Acre	4.50	1.00	4.50	4.50	1.00	4.50
Insecticide	Acre	3.50	1.00	3.50	3.50	1.00	3.50
Interest Annual Capital	Dol.	0.07	9.00	0.63	0.07	16.84	1.18
Labor	Hr.	1.50	2.09	3.14	1.50	2.09	3.14
Total Specified Costs	Dol.			41.95			58.40
			Sandy Loam Soils				
Production							
Silage	Ton	5.50	11.00	60.50	5.50	19.00	104.50
Gross Returns	Dol.	-	-	60.50	-	-	104.50
Inputs							
Seed	Lb.	0.25	20.00	5.00	0.25	20.00	5.00
Fertilizer N Pre Plant +							
Side Dress	Lb.	0.045	85.00	3.82	0.045	170.00	7.65
N in Water	Lb.	0.10	40.00	4.00	0.10	50.00	5.00
P_2O_5	Lb.	0.08	25.00	2.00	0.08	60.00	4.80
Crop Insurance	$100	11.00	0.46	5.06	11.00	0.80	8.80
Power & Machinery (Oper.)	Hr.	1.11	3.66	4.06	1.11	3.66	4.06
Power & Machinery (Fixed)	Hr.	0.99	3.66	3.62	0.99	3.66	3.62
Herbicide	Acre	4.50	1.00	4.50	4.50	1.00	4.50
Insecticide	Acre	3.50	1.00	3.50	3.50	1.00	3.50
Interest Annual Capital	Dol.	0.07	10.06	0.70	0.07	16.21	1.13
Labor	Hr.	1.50	2.09	3.14	1.50	2.09	3.14
Total Specified Costs	Dol.			39.40			51.20

TABLE XXXIX

ALFALFA HAY: PRODUCTION COSTS AND RETURNS PER ACRE ON CLAY LOAM AND SANDY LOAM SOILS EXCLUDING WATER COSTS

		Dryland			Inches of Irrigation Water					
						20"			33"	
Item	Unit	Price or Cost Per Unit	Quantity	Value or Cost	Price or Cost Per Unit	Quantity	Value or Cost	Price or Cost Per Unit	Quantity	Value or Cost
				Clay Loam Soils						
Production										
Hay	Ton	22.60	1.55	35.03	22.60	5.00	113.00	22.60	7.50	169.50
Gross Return	Dol.	-	-	35.03	-	-	113.00	-	-	169.50
Inputs										
Establishing	Acre	7.23	1.00	7.23	10.59	1.00	10.59	10.59	1.00	10.59
Fertilizer P_2O_5	Lb.	0.08	10.00	0.80	0.80	100.00	8.00	0.08	100.00	8.00
Insecticide	Lb.	2.50	0.50	1.25	2.50	0.50	1.25	2.50	0.50	1.25
Harvesting										
Swathing	Cutg.	3.00	3.00	9.00	3.00	5.00	15.00	3.00	5.00	15.00
Baling	Bale	0.15	59.00	8.85	0.15	150.00	22.50	0.15	225.00	33.75
Hauling	Bale	0.12	59.00	7.08	0.12	150.00	18.00	0.12	225.00	27.00
Interest Annual Capital	Dol.	0.07	7.29	0.51	0.07	24.45	1.71	0.07	33.49	2.34
Labor	Hr.	1.50	0.47	0.70	1.50	0.72	1.08	1.50	0.74	1.11
Total Specified Costs	Dol.			35.42			78.13			72.68
				Sandy Loam Soils						
Production										
Hay	Ton	22.60	1.75	39.55	22.60	5.00	113.00	22.60	7.50	169.50
Gross Return	Dol.	-	-	39.55	-	-	113.00	-	-	169.50
Inputs										
Establishing	Acre	7.23	1.00	7.23	10.59	1.00	10.59	10.59	1.00	10.59
Fertilizer P_2O_5	Lb.	0.08	10.00	0.80	0.80	140.00	11.20	0.08	140.00	11.20
Insecticide	Lb.	2.50	0.50	1.25	2.50	0.50	1.25	2.50	0.50	1.25
Swathing	Cutg.	3.00	3.00	9.00	3.00	5.00	15.00	3.00	5.00	15.00
Baling	Bale	0.15	66.00	9.90	0.15	150.00	22.50	0.15	225.00	33.75
Hauling	Bale	0.12	66.00	7.92	0.12	150.00	18.00	0.12	225.00	27.00
Interest Annual Capital	Dol.	0.07	7.30	0.51	0.07	25.79	1.79	0.07	34.83	2.44
Labor	Hr.	1.50	0.47	0.70	1.50	0.72	1.08	1.50	0.74	1.11
Total Specified Costs	Dol.			37.31			81.43			69.38

TABLE XL

COTTON: PRODUCTION COSTS AND RETURNS PER ACRE ON DRYLAND AND IRRIGATED CLAY LOAM AND SANDY LOAM SOILS EXCLUDING WATER COSTS

		Dryland			Inches of Irrigation Water					
						10"			18"	
Item	Unit	Price or Cost Per Unit	Quan-tity	Value or Cost	Price or Cost Per Unit	Quan-tity	Value or Cost	Price or Cost Per Unit	Quan-tity	Value or Cost
Clay Loam Soils										
Production										
Lint	Lb.	0.24	250.00	60.00	0.24	675.00	162.00	0.24	800.00	192.00
Seed	Ton	48.00	0.197	9.46	48.00	0.533	25.58	48.00	0.632	30.34
Gross Returns	Dol.	-	-	69.46	-	-	187.58	-	-	222.34
Inputs										
Seed	Lb.	0.08	21.00	1.68	0.08	35.00	2.80	0.08	35.00	2.80
Fertilizer N	Lb.	0.07	12.00	0.84	0.07	40.00	2.80	0.07	70.00	4.90
P	Lb.	-	-	-	0.08	20.00	1.60	0.08	40.00	3.20
Fertilizer Equipment	Acre	-	-	-	0.50	1.00	0.50	0.50	1.00	0.50
Crop Insurance	Acre	1.23	1.00	1.23	3.34	1.00	3.34	4.46	1.00	4.46
Power & Machinery (Oper.)	Hr.	0.56	4.33	2.42	0.56	7.77	4.35	0.56	8.06	4.51
Power & Machinery (Fixed)	Hr.	0.304	4.43	1.35	0.086	63.45	5.46	0.075	108.26	8.12
Hoeing & Chopping	Acre	3.30	1.00	3.30	3.75	1.00	3.75	4.50	1.00	4.50
Insecticide	Acre	0.75	1.00	0.75	4.50	1.00	4.50	5.10	1.00	5.10
Harvesting										
Stripping	Cwt.	0.75	9.56	7.17	0.75	25.84	19.38	0.75	30.62	22.96
Ginning	Cwt.	1.00	9.56	9.56	1.00	25.84	25.84	1.00	30.62	30.62
Hauling	Cwt.	0.25	9.56	2.39	0.25	25.84	6.46	0.25	30.62	7.66
Interest Annual Capital	Dol.	0.07	18.07	1.26	0.07	53.79	3.76	0.07	77.78	5.44
Labor	Hr.	1.50	2.40	3.60						
Total Specified Costs	Dol.			35.55			84.55			104.77
Sandy Loam Soils										
Production										
Lint	Lb.	0.24	130.00	31.20	0.24	575.00	138.00	0.24	750.00	180.00
Seed	Ton	48.00	0.100	4.80	45.00	0.455	21.84	48.00	0.59	28.32
Gross Returns	Dol.	-	-	36.00	-	-	159.84	-	-	208.32
Inputs										
Seed	Bu.	0.08	25.00	2.00	0.08	31.25	2.50	0.08	37.50	3.00
Fertilizer N	Lb.	-	-	-	0.10	30.00	3.00	0.10	60.00	6.00
Fertilizer Equipment	Acre	-	-	-	0.50	1.00	0.50	0.50	1.00	0.50
Crop Insurance	Acre	1.18	1.00	1.18	3.22	1.00	3.22	4.41	1.00	4.41
Power & Machinery (Oper.)	Hr.	0.56	2.44	1.36	0.56	8.64	4.84	0.56	8.91	4.99
Power & Machinery (Fixed)	Hr.	0.302	4.34	1.31	0.13	46.86	6.09	0.116	81.11	9.40
Hoeing & Chopping	Acre	3.30	1.00	3.30	3.75	1.00	3.75	4.50	1.00	4.50
Insecticide	Acre	0.75	1.00	0.75	4.50	1.00	4.50	5.10	1.00	5.10
Harvesting										
Stripping	Cwt.	0.75	4.98	3.74	0.75	22.00	16.50	0.75	28.72	21.54
Ginning	Cwt.	1.00	4.98	4.98	1.00	22.00	22.00	1.00	28.72	28.72
Hauling	Cwt.	0.25	4.98	1.25	0.25	22.00	5.50	0.25	28.72	7.18
Interest Annual Capital	Dol.	0.07	16.57	1.16	0.07	59.49	4.16	0.07	86.58	6.06
Labor	Hr.	1.50	2.40	3.60						
Total Specified Costs	Dol.			24.63			76.56			101.41

TABLE XLI

SOYBEANS: PRODUCTION COSTS AND RETURNS PER ACRE ON IRRIGATED CLAY LOAM AND SANDY LOAM SOILS EXCLUDING WATER COSTS

		Inches of Irrigation Water					
		Price or Cost Per Unit	16"		Price or Cost Per Unit	16"	
Item	Unit		Quantity	Value or Cost		Quantity	Value or Cost
		Clay Loam Soils			Sandy Loam Soils		
Production							
Soybeans	Bu.	2.27	35.00	79.45	2.27	35.00	79.45
Gross Returns	Dol.	-	-	79.45	-	-	79.45
Inputs							
Seed	Bu.	6.50	1.50	9.75	6.50	1.50	9.75
Fertilizer N	Lb.	0.07	45.00	3.15	0.07	60.00	4.20
P_2O_5	Lb.	0.08	-	-	0.08	10.00	0.80
Inoculation	Lb.	0.15	1.00	0.15	0.15	1.00	0.15
Crop Insurance	$100	12.00	0.70	8.40	12.00	0.70	8.40
Power & Machinery (Oper.)	Hr.	2.21	2.30	5.08	2.21	2.30	5.08
Power & Machinery (Fixed)	Hr.	1.01	2.68	2.71	1.01	2.68	2.71
Harvesting	Acre	6.00	1.00	6.00	6.00	1.00	6.00
Hauling	Bu.	0.08	35.00	2.80	0.08	35.00	2.80
Interest Annual Capital	Dol.	0.07	8.71	0.61	0.07	10.16	0.75
Labor	Hr.	1.50	1.56	2.34	1.50	1.56	2.34
Total Specified Costs	Dol.			40.99			42.98

TABLE XLII

SUGAR BEETS: PRODUCTION COSTS AND RETURNS PER ACRE ON IRRIGATED CLAY LOAM AND SANDY LOAM SOILS EXCLUDING WATER COSTS[1]

		Inches of Irrigation Water					
		Price or Cost Per Unit	26"		Price or Cost Per Unit	26"	
Item	Unit		Quantity	Value or Cost		Quantity	Value or Cost
			Clay Loam Soils			Sandy Loam Soils	
Production							
Beets	Ton	12.50	20.00	250.00	12.50	20.00	250.00
Gross Returns	Dol.	-	-	250.00	-	-	250.00
Inputs							
Labor	Hr.	1.50	4.01	6.01	1.50	3.21	4.82
Interest Annual Capital	Dol.	0.07	67.83	4.75	0.07	67.83	4.75
Other Inputs[2]	Dol.	-	-	79.17	-	-	79.17
Total Specified Costs	Dol.			89.93			88.74

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[1] Source: Grandin, Thomas B., Jr., Economics of Irrigation Development on Farms in the High Plains of Colorado, (Unpublished M.S. Thesis, Colorado State University, 1967), p. 143.

[2] Convenient breakdown of inputs other than capital and labor were not available.

TABLE XLIII

ASSUMED MONTHLY IRRIGATION WATER REQUIREMENTS FOR EACH CROP ENTERPRISE

Crop	Total	Acre-Inches of Water Applied								
	Applied	March	April	May	June	July	August	September	October	November
Wheat	8		2	2				4		
	18		3	6				5		4
Alfalfa	20		5	5	5	5				
	33		6	5	5	6	6	5		
Corn Silage	10			4			6			
	24			4	6	6	8			
Corn Grain	20		4		4	6	6			
	24		4		5	6	6	3		
Soybeans	16				4		6	6		
Grain Sorghum	16			2	2	4	8			
	24			2	6	8	8			
Cotton	10					4	6			
	18					9	9			

APPENDIX F

PUMPING AND DISTRIBUTION COSTS OF WATER

APPENDIX F

PUMPING AND DISTRIBUTION COSTS OF WATER

This appendix briefly presents the assumptions and values of the key parameters Shaffer and Eidman used to develop the cost estimates of the irrigation systems presented in Tables XLIV and XLV.

Well Costs

The investment costs of a new well include drilling, gravel packing and casing. The wells are assumed to be drilled to the bed rock at a cost of \$12.50 per foot of depth. For tax purposes wells were assumed to have a life span of 15 years and depreciated by the straight line method. An advalorem tax of \$0.0258 per g.p.m. is levied on each well.

Pump Costs

Pump costs were determined from the costs of the various components, column pipes, shafts, bowles and right angles required to maintain a certain level of well discharge at a given *total dynamic head*. An eight-inch column pipe and a one and one-half inch column shaft is used for all wells discharging greater than 500 g.p.m. A six-inch column pipe is used for all wells discharging less than 500 g.p.m. The size of the shaft for such small capacity wells is adjusted on the basis of total dynamic head. A 1 3/8 inch column shaft is used for a total dynamic head less than 325 feet. For total dynamic heads greater than 325 feet a 1 1/2 inch column shaft is used. The column pipe and shaft are connected in 20 feet sections down to the drawdown level.

Operating costs for the pump are based upon estimated repair costs equal to one-half of the new cost divided by its estimated life of 30,000 hours of operation. The pump is depreciated on the basis of this estimated life and taxed at the rate of $0.0086 per dollar of its original value.

Engine Costs

Natural gas engines are assumed as the power unit since more than 80 percent of the engines in the area operate on natural gas. Engine costs are based on brake horsepower which is defined as the following relation

$$BHP = \frac{GPM \times TDH}{PE \times DE}$$

Where:

BHP = brake horsepower,
GPM = well discharge in GPM,
TDH = total dynamic head,
PE = pump efficiency, and
DE = drive efficiency.

Pump efficiency and drive efficiency are assumed to be 65 percent and 95 percent, respectively. An original investment cost of $20.00 per brake horsepower is used.

Distribution Costs

The investment cost of the distribution system includes the cost of (1) the main line, (2) the lateral lines and (3) the valves between the two lines. Depreciation was scheduled over 15 years for aluminum and steel mainline pipes. Cement asbestos and plastic mainline pipes were depreciated over an estimated life of 20 years.

The surface system uses 600 feet of non-gated pipe and 1,400 feet of gated pipe. The self-propelled sprinkler system assumes a 930 foot or ten-tower lateral and 2,600 feet of underground plastic mainline pipe for wells with a capacity of 500 g.p.m. or less. A 2,600 foot underground aluminum mainline and a 1,285 foot or 13-tower lateral on wells with a capacity of greater than 500 g.p.m. is assumed.

Operating Costs

Fuel costs are based on natural gas consumption of 0.011 thousand cubic feet per brake horsepower. Lubrication costs were computed on the basis of 0.001 gallons of oil per water horsepower and grease of $0.01 per hour of operation. Plant maintenance labor is assumed at six percent of actual operation and charged at the rate of $2.50 per hour. Engine repairs were based on $0.0013 per brake horsepower hour. Pump repair costs per hour of operation were estimated to be equal to 50 percent of the per hour depreciation cost of the pumps.

Labor requirements for applying water were assumed to be 0.49 hours per acre irrigated with a surface system and 0.065 hours per acre irrigated with a self-propelled sprinkler system. Labor costs were charged at the rate of $1.50 per hour.

Maintenance of the distribution system was estimated as five percent of the original system cost divided by the hours of annual use for both surface and sprinkler systems.

TABLE XLIV

PUMPING AND DISTRIBUTION COSTS PER ACRE INCH FOR A FURROW IRRIGATION SYSTEM USING NATURAL GAS[1]

Well Capacity in g.p.m. / Well Depth	50		100		150		200		250		300		350		400		450		500	
	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total
75 Ft.	0.83	3.06	0.69	2.56	0.55	2.06	0.41	1.56	0.33	1.25	0.27	1.05	0.25	0.97	0.21	0.85	0.19	0.77	0.18	0.71
125	0.89	3.12	0.75	2.62	0.61	2.12	0.46	1.61	0.37	1.29	0.31	1.09	0.27	0.99	0.24	0.88	0.21	0.79	0.19	0.72
175	0.95	3.18	0.81	2.68	0.68	2.19	0.51	2.06	0.41	1.33	0.34	1.12	0.29	1.01	0.26	0.90	0.23	0.81	0.21	0.74
225	1.02	3.25	0.88	2.75	0.74	2.25	0.56	1.71	0.45	1.37	0.37	1.15	0.32	1.04	0.28	0.92	0.24	0.82	0.23	0.76
275	1.09	3.32	0.95	2.82	0.81	2.32	0.61	1.76	0.49	1.41	0.41	1.19	0.38	1.10	0.34	0.98	0.30	0.88	0.28	0.81
325	1.15	3.38	1.01	2.88	0.87	2.38	0.65	1.80	0.52	1.44	0.44	1.22	0.41	1.13	0.37	1.01	0.33	0.91	0.30	0.83
375	1.22	3.45	1.08	2.95	0.93	2.44	0.70	1.85	0.56	1.48	0.47	1.25	0.44	1.16	0.39	1.03	0.35	0.93	0.31	0.84
425	1.29	3.52	1.14	3.01	1.00	2.51	0.75	1.90	0.60	1.52	0.50	1.28	0.47	1.19	0.41	1.05	0.37	0.95	0.33	0.86
475	1.36	3.59	1.21	3.08	1.06	2.57	0.80	1.95	0.64	1.56	0.53	1.31	0.51	1.23	0.44	1.08	0.39	0.97	0.35	0.88
525	1.43	3.66	1.28	3.15	1.13	2.64	0.85	2.00	0.68	1.60	0.57	1.35	0.53	1.25	0.46	1.10	0.41	0.99	0.37	0.90
575	1.50	3.73	1.35	3.22	1.19	2.70	0.89	2.04	0.72	1.64	0.60	1.38	0.55	1.27	0.48	1.12	0.43	1.01	0.39	0.92
625	1.57	3.80	1.42	3.29	1.25	2.76	0.94	2.09	0.75	1.67	0.63	1.41	0.58	1.30	0.51	1.15	0.45	1.03	0.42	0.95
675	1.64	3.87	1.49	3.36	1.35	2.86	0.99	2.14	0.79	1.51	0.66	1.44	0.60	1.32	0.54	1.18	0.47	1.05	0.43	0.96
725	1.71	3.94	1.56	3.43	1.43	2.94	1.04	2.19	0.85	1.77	0.69	1.47	0.62	1.34	0.57	1.21	0.50	1.08	0.45	0.98
775	1.78	4.01	1.63	3.50	1.50	3.01	1.08	2.23	0.91	1.83	0.72	1.50	0.65	1.37	0.60	1.24	0.52	1.10	0.47	1.00
825	1.85	4.08	1.70	3.57	1.56	3.07	1.13	2.28	0.96	1.88	0.76	1.54	0.67	1.39	0.63	1.27	0.54	1.12	0.49	1.02
875	1.92	4.15	1.77	3.64	1.63	3.14	1.18	2.33	1.01	1.93	0.79	1.57	0.70	1.42	0.67	1.31	0.56	1.14	0.51	1.04
925	1.99	4.22	1.84	3.71	1.70	3.21	1.22	2.37	1.06	1.98	0.82	1.60	0.72	1.44	0.70	1.34	0.58	1.16	0.53	1.06

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[1] Entries are benchmark costs for zero pump lift. For any pump lift, total pumping and distribution cost is computed by multiplying pump lift in feet by $0.0016 and adding it to the appropriate (well depth, GPM) figure.

TABLE XLIV (Continued)

Well Capacity in g.p.m.	550		600		650		700		750		800		850		900		950		1000	
Well Depth	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total
75 Ft	0.17	0.66	0.15	0.60	0.14	0.56	0.15	0.53	0.14	0.50	0.13	0.47	0.12	0.44	0.12	0.43	0.11	0.40	0.11	0.38
125	0.18	0.67	0.17	0.62	0.16	0.58	0.16	0.54	0.15	0.51	0.14	0.48	0.14	0.46	0.13	0.44	0.12	0.41	0.12	0.39
175	0.20	0.69	0.19	0.64	0.18	0.60	0.18	0.56	0.17	0.53	0.16	0.50	0.15	0.47	0.14	0.45	0.13	0.42	0.13	0.40
225	0.22	0.71	0.21	0.66	0.20	0.62	0.19	0.57	0.18	0.54	0.17	0.51	0.16	0.48	0.15	0.46	0.14	0.43	0.13	0.40
275	0.25	0.74	0.23	0.68	0.22	0.64	0.20	0.58	0.19	0.55	0.18	0.52	0.17	0.49	0.16	0.47	0.15	0.44	0.14	0.41
325	0.27	0.76	0.25	0.70	0.23	0.65	0.22	0.60	0.20	0.56	0.19	0.53	0.18	0.50	0.17	0.48	0.16	0.45	0.15	0.42
375	0.29	0.78	0.26	0.71	0.25	0.67	0.23	0.61	0.22	0.58	0.20	0.54	0.19	0.51	0.18	0.49	0.17	0.46	0.16	0.43
425	0.30	0.79	0.28	0.73	0.26	0.68	0.25	0.63	0.23	0.59	0.22	0.56	0.20	0.52	0.19	0.50	0.18	0.47	0.17	0.44
475	0.32	0.81	0.30	0.75	0.28	0.70	0.26	0.64	0.24	0.60	0.23	0.57	0.21	0.53	0.20	0.51	0.19	0.48	0.18	0.45
525	0.34	0.83	0.31	0.76	0.29	0.71	0.27	0.65	0.26	0.62	0.24	0.58	0.23	0.55	0.21	0.52	0.20	0.49	0.19	0.46
575	0.36	0.85	0.33	0.78	0.30	0.72	0.29	0.67	0.27	0.63	0.25	0.59	0.24	0.56	0.22	0.53	0.21	0.50	0.20	0.47
625	0.37	0.86	0.34	0.79	0.32	0.74	0.30	0.68	0.28	0.64	0.26	0.60	0.25	0.57	0.24	0.55	0.22	0.51	0.21	0.48
675	0.39	0.88	0.36	0.81	0.33	0.75	0.31	0.69	0.29	0.65	0.28	0.62	0.26	0.58	0.25	0.56	0.23	0.52	0.22	0.49
725	0.41	0.90	0.38	0.83	0.35	0.77	0.33	0.71	0.31	0.67	0.29	0.63	0.27	0.59	0.26	0.57	0.24	0.53	0.23	0.50
775	0.43	0.92	0.40	0.85	0.37	0.79	0.35	0.73	0.33	0.69	0.31	0.65	0.28	0.60	0.27	0.58	0.25	0.54	0.24	0.51
825	0.45	0.94	0.42	0.87	0.39	0.81	0.37	0.75	0.35	0.71	0.33	0.67	0.29	0.61	0.28	0.59	0.26	0.55	0.25	0.52
875	0.47	0.96	0.44	0.89	0.41	0.83	0.39	0.77	0.37	0.73	0.35	0.69	0.30	0.62	0.29	0.60	0.27	0.56	0.26	0.53
925	0.49	0.98	0.46	0.91	0.43	0.85	0.41	0.79	0.39	0.75	0.37	0.71	0.31	0.64	0.30	0.61	0.28	0.57	0.27	0.54

TABLE XLV

PUMPING AND DISTRIBUTION COSTS PER ACRE INCH FOR A SELF-PROPELLED IRRIGATION SYSTEM USING NATURAL GAS[1]

Well Capacity in g.p.m.	50		100		150		200		250		300		350		400		450		500	
Well Depth	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total
75 Ft.	2.78	5.25	2.32	4.40	1.86	3.55	1.40	2.70	1.13	2.20	0.95	1.87	1.07	2.05	0.91	1.77	0.81	1.59	0.73	1.44
125	2.84	5.31	2.38	4.44	1.92	3.61	1.45	2.75	1.17	2.27	0.98	1.90	1.10	2.08	0.94	1.80	0.84	1.62	0.75	1.46
175	2.91	5.38	2.45	4.53	1.99	3.68	1.49	2.79	1.21	2.28	1.02	1.94	1.14	2.12	0.98	1.84	0.88	1.66	0.79	1.50
225	2.97	5.45	2.51	4.59	2.05	3.74	1.54	2.84	1.25	2.32	1.05	1.97	1.17	2.15	1.01	1.87	0.91	1.69	0.82	1.53
275	3.04	5.51	2.58	4.66	2.12	3.81	1.59	2.89	1.28	2.35	1.08	2.00	1.20	2.18	1.04	1.90	0.94	1.72	0.85	1.56
325	3.10	5.57	2.64	4.72	2.18	3.87	1.64	2.94	1.32	2.39	1.11	2.03	1.23	2.21	1.07	1.93	0.96	1.74	0.87	1.58
375	3.16	5.63	2.70	4.78	2.24	3.93	1.68	2.98	1.36	2.43	1.14	2.06	1.26	2.24	1.09	1.95	0.98	1.76	0.89	1.60
425	3.23	5.70	2.77	4.85	2.31	4.00	1.73	3.03	1.42	2.49	1.18	2.10	1.28	2.26	1.12	1.98	1.00	1.78	0.91	1.62
475	3.29	5.76	2.83	4.91	2.37	4.06	1.78	3.08	1.44	2.51	1.21	2.13	1.31	2.29	1.15	2.01	1.02	1.80	0.93	1.64
525	3.36	5.83	2.90	4.98	2.44	4.13	1.83	3.13	1.48	2.55	1.24	2.16	1.34	2.32	1.17	2.03	1.04	1.82	0.95	1.66
575	3.43	5.90	2.97	5.05	2.50	4.19	1.88	3.18	1.54	2.61	1.27	2.19	1.37	2.35	1.19	2.05	1.07	1.85	0.97	1.68
625	3.49	5.96	3.03	5.11	2.56	4.25	1.92	3.22	1.55	2.62	1.32	2.24	1.39	2.37	1.21	2.07	1.09	1.87	0.98	1.69
675	3.55	6.02	3.09	5.17	2.63	4.32	1.98	3.28	1.60	2.67	1.35	2.27	1.42	2.40	1.24	2.10	1.11	1.89	1.01	1.72
725	3.62	6.09	3.16	5.24	2.69	4.38	2.05	3.35	1.67	2.74	1.42	2.34	1.45	2.43	1.28	2.14	1.15	1.93	1.04	1.75
775	3.69	6.16	3.23	5.31	2.75	4.44	2.11	3.41	1.73	2.80	1.48	2.40	1.47	2.45	1.31	2.17	1.18	1.96	1.07	1.78
825	3.75	6.22	3.29	5.37	2.82	4.51	2.18	3.48	1.80	2.87	1.55	2.47	1.50	2.48	1.35	2.21	1.20	1.98	1.10	1.81
875	3.81	6.28	3.35	5.43	2.88	4.57	2.24	3.54	1.86	2.93	1.61	2.53	1.52	2.50	1.38	2.24	1.23	2.01	1.12	1.83
925	3.87	6.34	3.42	5.50	2.95	4.64	2.31	3.61	1.93	3.00	1.68	2.60	1.55	2.53	1.42	2.28	1.25	2.03	1.15	1.86

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[1] Entries are benchmark costs for zero pump lift. For any pump lift, total pumping and distribution cost is computed by multiplying pump lift in feet by $0.0016 and adding it to the appropriate (well depth, GPM) figure.

TABLE XLV (Continued)

Well Capacity in g.p.m.	550		600		650		700		750		800		850		900		950		1000	
Well Depth	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total	Fixed	Total
75 Ft.	0.65	1.31	0.67	1.29	0.61	1.19	0.72	1.40	0.68	1.33	0.64	1.27	0.63	1.24	0.60	1.20	0.56	1.14	0.54	1.11
125	0.68	1.34	0.68	1.30	0.62	1.20	0.73	1.41	0.69	1.34	0.65	1.28	0.65	1.26	0.61	1.21	0.57	1.15	0.55	1.12
175	0.72	1.38	0.69	1.31	0.63	1.21	0.74	1.42	0.70	1.35	0.66	1.29	0.66	1.27	0.63	1.23	0.59	1.17	0.57	1.14
225	0.75	1.41	0.71	1.33	0.65	1.23	0.76	1.44	0.71	1.36	0.68	1.31	0.67	1.28	0.64	1.24	0.60	1.18	0.58	1.15
275	0.78	1.44	0.72	1.34	0.66	1.24	0.77	1.45	0.72	1.37	0.69	1.32	0.68	1.29	0.65	1.25	0.61	1.19	0.59	1.16
325	0.79	1.45	0.74	1.36	0.68	1.26	0.78	1.46	0.73	1.38	0.70	1.33	0.69	1.30	0.66	1.26	0.62	1.20	0.60	1.17
375	0.81	1.47	0.75	1.37	0.70	1.28	0.80	1.48	0.74	1.39	0.71	1.34	0.70	1.31	0.67	1.27	0.63	1.21	0.61	1.18
425	0.83	1.49	0.77	1.39	0.71	1.29	0.81	1.49	0.75	1.40	0.72	1.35	0.71	1.32	0.68	1.28	0.64	1.22	0.62	1.19
475	0.85	1.51	0.78	1.40	0.72	1.30	0.83	1.51	0.76	1.41	0.74	1.37	0.72	1.33	0.69	1.29	0.65	1.23	0.63	1.20
525	0.87	1.53	0.80	1.42	0.74	1.32	0.84	1.52	0.78	1.43	0.75	1.38	0.73	1.34	0.70	1.30	0.66	1.24	0.64	1.21
575	0.87	1.53	0.83	1.45	0.76	1.34	0.85	1.53	0.80	1.45	0.76	1.39	0.74	1.35	0.71	1.31	0.67	1.25	0.65	1.22
625	0.90	1.56	0.86	1.48	0.77	1.35	0.87	1.55	0.82	1.47	0.77	1.40	0.76	1.37	0.72	1.32	0.68	1.26	0.66	1.23
675	0.92	1.58	0.89	1.51	0.79	1.37	0.88	1.56	0.83	1.48	0.79	1.42	0.77	1.38	0.73	1.33	0.69	1.27	0.67	1.24
725	0.95	1.61	0.92	1.54	0.82	1.40	0.89	1.57	0.84	1.49	0.80	1.43	0.78	1.39	0.75	1.35	0.71	1.29	0.69	1.26
775	0.98	1.64	0.95	1.57	0.85	1.43	0.91	1.59	0.86	1.51	0.82	1.45	0.80	1.41	0.77	1.37	0.72	1.30	0.70	1.27
825	1.00	1.66	0.97	1.59	0.87	1.45	0.92	1.60	0.87	1.52	0.83	1.46	0.81	1.42	0.78	1.38	0.73	1.31	0.71	1.28
875	1.03	1.69	1.00	1.62	0.90	1.48	0.93	1.61	0.88	1.53	0.84	1.47	0.82	1.43	0.79	1.39	0.74	1.32	0.72	1.29
925	1.06	1.72	1.03	1.65	0.93	1.51	0.95	1.63	0.90	1.55	0.86	1.49	0.84	1.45	0.81	1.41	0.76	1.34	0.74	1.31

FOOTNOTES

[1] John W. Green, Vernon R. Eidman, and Larry R. Peters, *Alternative Irrigated Crop Enterprises on Clay and Sandy Loam Soils of the Oklahoma Panhandle: Resource Requirements, Costs and Returns*, Oklahoma Agricultural Experiment Station, Stillwater, Oklahoma, Processed Series P-544 (March, 1967).

[2] D. S. Moore, K. R. Tefertiller, W. F. Hughes and R. H. Rogers, *Production Requirements, Costs and Expected Returns for Crop Enterprises: Hardland Soils - High Plains of Texas*, Texas Agricultural Experiment Station, MP-601 (August, 1962), and Larry J. Connor, W. F. Lagrone, and J. S. Plaxico, *Resource Requirements, Costs and Expected Returns; Alternative Crop and Livestock Enterprises: Loam Soils of the Rolling Plains of South Western Oklahoma*, Oklahoma Agricultural Experiment Station, Stillwater, Oklahoma, Processed Series P-368 (February, 1969).

[3] Thomas B. Grandin, Jr., "Economics of Irrigation Development on Farms in the High Plains of Colorado", (unpublished M.S. Thesis, Colorado State University, 1967), p. 143, and Loren E. Whipps, "Economics of Irrigation - 1969", (unpublished mimeo., South Western Kansas District Extension Economist: Farm Management).

APPENDIX G

TABLE XLVI

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 0-100 FT. IN MODEL A

Input State S_i	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in million ac. ft.									
		0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
		Undiscounted Annual Net Returns in Million Dollars									
1	20	10.78	12.43	13.72	15.01	16.29	17.58	18.58	19.71	20.12	20.56
2	19	10.78	12.42	13.71	15.00	16.27	17.55	18.55	19.67	20.06	20.49
3	18	10.78	12.42	13.70	14.98	16.25	17.52	18.49	19.61	19.97	20.39
4	17	10.78	12.41	13.69	14.97	16.21	17.48	18.43	19.53	19.91	30.32
5	16	10.78	12.41	13.67	14.94	16.17	17.43	18.38	19.47	19.89	20.30
6	15	10.78	12.40	13.65	14.91	16.13	17.38	18.37	19.46	19.69	20.08
7	14	10.78	12.39	13.63	14.88	16.13	17.38	18.21	19.28	-[a]	-
8	13	10.78	12.38	13.63	14.88	16.02	17.25	-	-	-	-
9	12	10.78	12.38	13.58	14.80	-	-	-	-	-	-
10	11	10.78	12.35	3.92	0.32	-	-	-	-	-	-

[a] (-) entries indicate that net returns will be negative if those decisions are made in the corresponding state.

TABLE XLVII

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 101-200 FT. IN MODEL A

Input State S_i	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in million ac. ft.									
		0	1	2	3	4	5	6	7	8	9
		Undiscounted Annual Net Returns in Million Dollars									
1	53-57	10.07	13.17	15.79	18.22	19.77	20.61	21.37	21.92	22.42	22.93
2	48-52	10.07	13.16	15.76	18.18	19.72	20.56	21.31	21.85	22.35	22.85
3	43-47	10.07	13.14	15.74	18.14	19.67	20.45	21.18	21.70	22.19	22.67
4	38-42	10.07	13.12	15.70	18.08	19.58	20.32	21.02	21.52	21.99	22.47
5	33.37	10.07	13.10	15.65	18.01	19.48	20.24	27.93	21.41	21.87	22.32
6	28-32	10.07	13.08	15.61	17.95	19.40	19.93	27.55	20.99	21.40	21.82
7	23-27	10.07	13.01	15.48	17.76	19.15	19.38	26.86	20.21	20.55	20.89
8	18-22	10.07	12.90	15.26	17.43	18.68	19.11	26.53	19.83	20.13	20.44
9	13-17	10.07	12.84	15.15	17.27	18.46	-[a]	-	-	-	-
10	0-12	10.07	3.34	-	-	-	-	-	-	-	-

[a] (-) entries indicate that net returns will be negative if those decisions are made in the corresponding state.

TABLE XLVIII

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 201-300 FT. IN MODEL A

Input State S_i	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in million ac. ft. 0	1	2	3	4	5	6	7	8	9
		Undiscounted Annual Net Returns in Million Dollars									
1	104-108	11.58	14.74	17.36	19.97	22.15	23.03	23.91	24.66	25.19	25.70
2	99-103	11.58	14.74	17.35	19.95	22.12	22.99	23.87	24.61	25.14	25.64
3	94-98	11.58	14.73	17.33	19.92	22.09	22.96	23.84	24.57	25.09	25.59
4	89-93	11.58	14.72	17.32	19.91	22.06	22.92	23.80	24.53	25.04	25.54
5	84-88	11.58	14.71	17.30	19.88	22.02	22.85	23.72	24.43	24.94	25.42
6	79-83	11.58	14.70	17.28	19.84	21.97	22.80	23.66	24.36	24.86	25.34
7	74-78	11.58	14.69	17.26	19.81	21.93	22.74	23.59	24.27	24.77	25.24
8	69-73	11.58	14.68	17.23	19.77	21.88	22.60	23.43	24.07	24.55	25.01
9	64-68	11.58	14.65	17.18	19.69	21.78	22.56	23.39	24.04	24.51	24.96
10	59-63	11.58	14.64	17.16	19.66	21.74	22.42	23.23	23.84	24.29	24.73
11	54-58	11.58	14.61	17.10	19.58	21.63	22.21	22.99	23.56	23.98	24.40
12	49-53	11.58	14.57	17.02	19.46	21.47	21.88	22.62	23.10	23.48	23.85
13	44-48	11.58	14.50	16.89	19.27	21.21	21.85	22.59	23.06	23.44	23.80
14	39-43	11.58	14.50	16.88	19.25	21.19	21.52	22.22	22.62	22.94	23.26
15	34-38	11.58	14.43	16.76	19.06	20.94	21.37	22.04	22.39	22.68	22.98
16	29-33	11.58	14.41	16.71	18.99	20.84	21.27	21.92	22.24	22.52	22.80
17	0-28	11.58	4.92	-[a]	-	-	-	-	-	-	-

[a] (-) entries indicate that net returns will be negative if those decisions are made in the corresponding state.

TABLE XLIX

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 301-400 FT. IN MODEL A

Input State S_i	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in million ac. ft. 0	1	2	3	4	5	6	7	8
		Undiscounted Annual Net Returns in Million Dollars								
1	98-102	9.35	12.04	15.01	17.03	18.51	19.34	20.00	20.51	21.02
2	93-97	9.35	12.03	14.99	17.00	18.48	19.30	19.95	20.46	20.97
3	88-92	9.35	12.03	14.97	16.98	18.44	19.26	19.90	20.40	20.90
4	83-87	9.35	12.02	14.95	16.95	18.41	19.23	19.86	20.36	20.85
5	78-82	9.35	12.01	14.94	16.93	18.38	19.18	19.81	20.29	20.77
6	73-77	9.35	12.00	14.93	16.91	18.34	19.09	19.70	20.17	20.65
7	68-72	9.35	11.98	14.88	16.84	18.26	19.02	19.61	20.08	20.55
8	63-67	9.35	11.97	14.85	16.80	18.20	18.92	19.49	19.95	20.41
9	58-62	9.35	11.95	14.82	16.75	18.12	18.88	19.45	19.90	20.35
10	53-57	9.35	11.94	14.79	16.71	18.09	18.81	19.36	19.81	20.26
11	48-52	9.35	11.92	14.76	16.67	18.03	18.68	19.20	19.63	20.06
12	43-47	9.35	11.90	14.71	16.59	17.92	18.45	18.92	19.32	19.72
13	38-42	9.35	11.85	14.61	16.45	17.72	18.20	18.61	18.97	19.34
14	33-37	9.35	11.80	14.51	16.29	17.50	18.02	18.39	18.73	19.08
15	28-32	9.35	11.77	14.44	16.19	17.36	17.86	18.19	18.51	18.83
16	0-27	9.35	11.74	14.37	16.09	17.22	17.72	18.01	18.31	18.61

TABLE L

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 401-500 FT. IN MODEL A

Input State S_i	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in million ac. ft.			
		0	1	2	3
		Undiscounted Annual Net Returns in Million Dollars			
1	44-48	3.48	6.21	7.35	7.90
2	39-43	3.48	6.19	7.32	7.85
3	34-38	3.48	6.17	7.28	7.80
4	29-33	3.48	6.16	7.25	7.76
5	24-28	3.48	6.11	7.16	7.64
6	19-23	3.48	6.08	7.10	7.55
7	14-18	3.48	6.00	6.94	7.34
8	9-13	3.48	5.91	6.76	7.09
9	4-8	3.48	5.82	6.59	6.87
10	0-3	3.48	5.79	6.52	6.76

TABLE LI

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 501-600 FT. IN MODEL A

Input State S_i	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in million ac. ft.				
		0	0.5	1.0	1.5	2.0
		Undiscounted Annual Net Returns in Million Dollars				
1	34-35	2.66	3.84	4.67	5.11	5.21
2	32-33	2.66	3.83	4.66	5.08	5.17
3	30-31	2.66	3.83	4.65	5.08	5.17
4	28-29	2.66	3.82	4.64	5.07	5.16
5	26-27	2.66	3.82	4.63	5.06	5.13
6	24-25	2.66	3.81	4.61	5.03	5.10
7	22-23	2.66	3.80	4.59	5.01	5.06
8	20-21	2.66	3.79	4.57	4.98	5.03
9	18-19	2.66	3.78	4.55	4.95	4.98
10	16-17	2.66	3.76	4.52	4.91	4.91
11	14-15	2.66	3.74	4.47	4.86	4.82
12	12-13	2.66	3.71	4.42	4.78	4.73
13	10-11	2.66	3.68	4.36	4.72	4.65
14	8-9	2.66	3.66	4.31	4.65	4.59
15	0-7	2.66	3.64	4.28	4.61	4.40

TABLE LII

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 0-100 FT. IN MODEL B

Input State S_i	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in Million Ac. Ft.										
		0	1	2	3	4	5	6	7	8	9	10
		Undiscounted Annual Net Returns in Million Dollars										
1	16-20	11.81	14.82	17.42	20.02	21.78	22.38	23.10	23.77	24.23	24.69	23.76
2	11-15	11.81	14.77	17.31	19.85	21.56	21.63	22.14	22.69	23.05	23.40	-[a]
3	6-10	11.81	14.61	17.01	19.41	20.96	-	-	-	-	-	-
4	0-5	11.81	4.92	-	-	-	-	-	-	-	-	-

[a] (-) entries indicate that net returns will be negative if those decisions are made in the corresponding state.

TABLE LIII

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 101-200 FT. IN MODEL B

Input State	Storage Level	Alternative Rate of Withdrawal Per Stage in Million Ac. Ft.															
S_i	mill.ac.ft.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Undiscounted Annual Net Returns in Million Dollars															
1	53-57	11.97	15.03	17.39	19.39	22.13	24.42	26.75	28.59	30.90	32.92	34.40	35.97	37.09	37.72	38.28	38.44
2	48-52	11.97	15.01	17.37	19.35	22.07	24.36	26.68	28.42	30.82	32.83	34.20	35.75	36.86	37.47	38.03	38.13
3	43-47	11.97	15.00	17.34	19.31	22.02	24.25	26.54	28.26	30.64	32.84	33.97	35.51	36.61	37.18	37.75	37.89
4	38-42	11.97	14.98	17.30	19.25	21.94	24.15	26.39	28.08	30.44	32.42	33.86	35.38	36.48	37.04	37.60	37.76
5	33-37	11.97	14.95	17.25	19.17	21.84	24.03	26.27	27.96	30.30	32.27	33.21	34.69	35.79	36.28	36.84	36.62
6	28-32	11.97	14.93	17.21	19.11	21.76	23.72	25.90	27.51	29.81	31.72	32.16	33.57	34.61	34.96	35.52	35.49
7	23-27	11.97	14.87	17.08	18.92	21.51	23.18	25.21	26.69	28.91	30.74	31.65	33.02	34.05	34.33	34.89	-[a]
8	18-22	11.97	14.75	16.85	18.59	21.07	22.91	24.88	26.30	28.48	30.26	-	-	-	-	-	-
9	0-17	11.97	14.69	16.75	18.43	20.85	-	-	-	-	-	-	-	-	-	-	-

[a] (-) entries indicate that net returns will be negative if these decisions are made in the corresponding states.

TABLE LIV

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 201-300 FT. IN MODEL B

Input State S_1	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in Million Ac. Ft.																					
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
		Undiscounted Annual Net Returns in Million Dollars																					
1	104-108	13.76	16.95	19.41	21.77	24.13	26.46	28.81	31.17	33.49	35.66	37.64	39.68	41.75	43.50	45.08	46.58	48.04	48.83	49.75	50.26	50.62	50.70
2	99-103	13.76	16.94	19.39	21.75	24.10	26.42	28.77	31.12	33.43	35.59	37.58	39.62	41.69	43.44	45.01	46.47	47.93	48.72	49.63	50.13	50.39	50.45
3	94-98	13.76	16.93	19.37	21.72	24.07	26.39	28.73	31.08	33.38	35.54	37.50	39.53	41.59	43.34	44.90	46.29	47.74	48.51	49.42	49.91	50.22	50.27
4	89-93	13.76	16.93	19.36	21.71	24.05	26.34	28.67	31.00	33.31	35.47	37.36	39.38	41.45	43.18	44.74	46.17	47.60	48.37	49.27	49.75	50.02	50.05
5	84-88	13.76	16.92	19.35	21.68	24.01	26.27	28.59	30.91	33.20	35.34	37.26	39.28	41.34	43.07	44.62	46.01	47.43	48.19	49.08	49.55	49.56	49.55
6	79-83	13.76	16.90	19.32	21.64	23.96	26.23	28.54	30.85	33.12	35.25	37.14	39.15	41.20	42.93	44.47	45.67	47.04	47.78	48.65	49.11	49.43	49.44
7	74-78	13.76	16.89	19.30	21.61	23.92	26.17	28.47	30.76	33.02	35.13	36.86	38.85	40.90	42.61	44.14	45.56	46.94	47.67	48.54	48.99	48.97	48.94
8	69-73	13.76	16.88	19.27	21.57	23.87	26.03	28.31	30.58	32.80	34.88	36.78	38.77	40.82	42.52	44.04	45.21	46.55	47.26	48.11	48.54	48.29	48.21
9	64-68	13.76	16.85	19.22	21.49	23.76	25.99	28.25	30.51	32.73	34.81	36.50	38.47	40.51	42.20	43.71	44.69	45.97	46.66	47.47	47.88	47.22	47.05
10	59-63	13.76	16.84	19.20	21.46	23.72	25.85	28.08	30.32	32.51	34.55	36.08	38.03	40.06	41.73	43.21	43.87	45.07	45.71	46.48	46.85	47.12	46.94
11	54-58	13.76	16.81	19.14	21.38	23.61	25.64	27.84	30.03	32.18	34.17	35.43	37.34	39.34	40.98	42.42	43.79	44.98	45.62	46.38	46.75	45.98	45.73
12	49-53	13.76	16.77	19.06	21.25	23.45	25.32	27.46	29.59	31.65	33.56	35.37	37.27	39.28	40.92	42.35	42.95	44.05	44.63	45.34	45.66	45.43	45.12
13	44-48	13.76	16.70	18.93	21.06	23.19	25.30	27.42	29.55	31.61	33.51	34.73	36.59	38.58	40.17	41.56	42.56	43.61	44.16	44.84	45.14	45.06	44.71
14	39-43	13.76	16.70	18.91	21.04	23.17	24.98	27.04	29.11	31.09	32.92	34.43	36.27	38.25	39.83	41.20	42.30	43.30	43.84	44.50	44.78	–[a]	–
15	34-38	13.76	16.63	18.78	20.85	22.91	24.86	26.90	28.94	30.88	32.65	34.23	36.06	38.04	39.60	40.95	–	–	–	–	–	–	–
16	29-33	13.76	16.60	18.73	20.77	22.81	24.76	26.79	28.82	30.72	32.47	–	–	–	–	–	–	–	–	–	–	–	–
17	0-28	13.76	16.58	18.69	20.71	22.74	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] (–) entries indicate that net returns will be negative if those decisions are made in the corresponding state.

TABLE LV

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 301-400 FT. IN MODEL B

Input State S_i	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in Million Ac. Ft.												
		0	1	2	3	4	5	6	7	8	9	10	11	12
		Undiscounted Annual Net Returns in Million Dollars												
1	98-102	8.45	10.93	13.44	15.00	16.19	16.92	17.67	18.41	19.16	20.32	22.69	25.42	27.85
2	93-97	8.45	10.93	13.43	14.99	16.17	16.90	17.64	18.38	19.13	20.28	22.64	25.36	27.77
3	88-92	8.45	10.92	13.42	14.98	16.15	16.87	17.61	18.35	19.09	20.24	22.58	25.29	27.70
4	83-87	8.45	10.92	13.41	14.96	16.14	16.85	17.58	18.31	19.04	20.18	22.47	25.18	27.58
5	78-82	8.45	10.92	13.40	14.95	16.11	16.79	17.51	18.23	18.95	20.08	22.38	25.06	27.44
6	73-77	8.45	10.91	13.39	14.92	16.07	16.75	17.47	18.18	18.89	20.01	22.30	24.97	27.33
7	68-72	8.45	10.90	13.37	14.89	16.04	16.72	17.43	18.13	18.84	19.95	22.16	24.81	27.15
8	63-67	8.45	10.89	13.35	14.87	16.01	16.65	17.35	18.04	18.74	19.84	22.10	24.74	27.08
9	58-62	8.45	10.89	13.33	14.83	15.96	16.63	17.32	18.00	18.69	19.78	22.06	24.69	27.01
10	53-57	8.45	10.88	13.32	14.82	15.94	16.62	17.30	17.99	18.67	19.76	21.86	24.45	26.74
11	48-52	8.45	10.87	13.31	14.81	15.93	16.52	17.19	17.86	18.52	19.59	21.53	24.08	26.32
12	43-47	8.45	10.85	13.27	14.75	15.85	16.37	17.00	17.64	18.27	19.31	21.18	23.67	25.86
13	38-42	8.45	10.83	13.22	14.66	15.73	16.21	16.82	17.42	18.03	19.02	20.92	23.38	25.52
14	33-37	8.45	10.80	13.16	14.57	15.61	16.09	16.67	17.26	17.84	18.81	20.67	23.09	25.20
15	28-32	8.45	10.77	13.11	14.50	15.51	15.98	16.54	17.09	17.65	18.60	20.46	22.84	24.92
16	23-27	8.45	10.75	13.06	14.43	15.42	15.88	16.41	16.95	17.49	18.41	-[a]	-	-
17	0-22	8.45	10.72	13.02	14.37	15.34	-	-	-	-	-	-	-	-

[a] (-) entries indicate that net returns will be negative if those decisions are made in the corresponding state.

TABLE LVI

UNDISCOUNTED ANNUAL STAGE RETURN MATRIX FOR SATURATED THICKNESS CLASS 501-600 FT. IN MODEL B

Input State S_i	Storage Level mill.ac.ft.	Alternative Rate of Withdrawal Per Stage in million ac. ft. 0	1	2	3	4
		Undiscounted Annual Net Returns in Million Dollars				
1	29-33	2.45	4.98	7.34	9.69	11.77
2	24-28	2.45	4.94	7.27	9.59	11.63
3	19-23	2.45	4.91	7.21	9.50	11.52
4	14-18	2.45	4.88	7.13	9.38	11.36
5	9-13	2.45	4.77	6.93	9.07	10.95
6	0-8	2.45	4.63	6.64	8.63	10.34

VITA

Solomon Bekure

Candidate for the Degree of

Doctor of Philosophy

Thesis: AN ECONOMIC ANALYSIS OF THE INTERTEMPORAL ALLOCATION OF GROUND WATER IN THE CENTRAL OGALLALA FORMATION

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in Hirna, Ethiopia, November 18, 1940, the son of Wolde G. and Itefwork K. Bekure.

Education: Graduated from Haile Selassie I Secondary School, Addis Ababa, Ethiopia, July, 1959; received the Bachelor of Science degree (Agriculture) from Haile Selassie I University, College of Agriculture, Alemaya, Ethiopia, July, 1963; received the Master of Science degree from Oklahoma State University in May, 1967, with a major in Agricultural Economics; completed requirements for the Doctor of Philosophy degree at Oklahoma State University in May, 1971.

Professional Experience: Graduate Research Assistant, Haile Selassie I University, July, 1963 to August, 1965. Research Fellow, Oklahoma State University, September, 1965 to July, 1967. Research Assistant, Oklahoma State University, August, 1967 to September, 1970.

Organizations: American Agricultural Economics Association; Association for the Advancement of Agricultural Sciences in Africa.