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Groundwater mining in the Ogallala Aquifer in relation to rising energy prices and agricultural production

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GROUNDWATER MINING IN THE OGALLALA AQUIFER IN RELATION TO RISING ENERGY PRICES AND AGRICULTURAL PRODUCTION

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Groundwater mining in the Ogallala Aquifer

in relation to rising energy prices and

agricultural production

by

Charles Cameron Short

A Dissertation Submitted to the

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Finally, I would like to thank my wife Joyce for her encouragement and support and dedicate this work to her and our children, Tara, Sebastian, and Morgan.

1. THE DEVELOPMENT OF THE OGALLALA AQUIFER

The Ogallala Aquifer is an unconfined fresh-water aquifer extending from just north of the Nebraska-South Dakota border to the southern edge of the Texas High Plains. The areal extent of the aquifer (Figures 1.1 and 1.2) includes the eastern tier of counties in Colorado and New Mexico, the western third of Kansas, three counties in Oklahoma, and the greater part of the state of Nebraska and the Texas "panhandle."

The last four decades have seen extensive development of irrigation in this area, primarily using water derived from the Ogallala Aquifer and sporadically occurring overlying alluvial aquifers. Because the amount of groundwater withdrawn greatly exceeds recharge, the water table has been falling throughout the area. The purpose of this dissertation is to analyze the consequences of the declining water for agricultural production in the area overlying the Ogallala Aquifer and for other regions within the contiguous states in a framework of interregional competition and rising energy prices.

1.1. Historical Development of the Ogallala Aquifer

The Ogallala Aquifer, like all aquifers, draws its name from the geological formation in which it is found.[1] The Ogallala Formation was deposited in the Pliocene Epoch from alluvial material originating in the Rocky Mountains. Subsequent erosion has isolated the formation

[1]The Ogallala Formation is named after a small town in Keith County, Nebraska. The town in turn derives its name from a clan of the Sioux Nation.

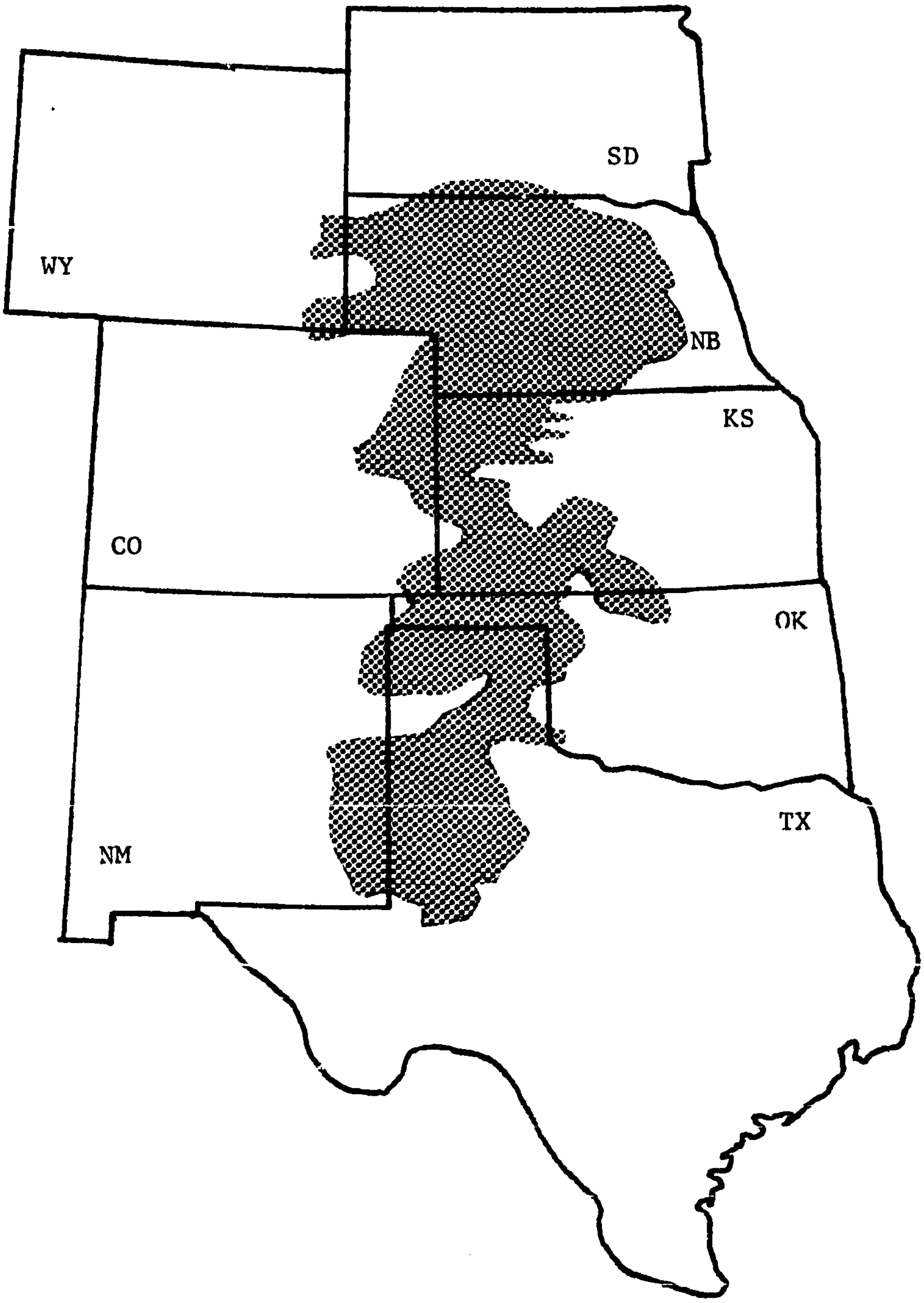

Figure 1.1. The Ogallala Aquifer (adapted from McGuinness, 1964)

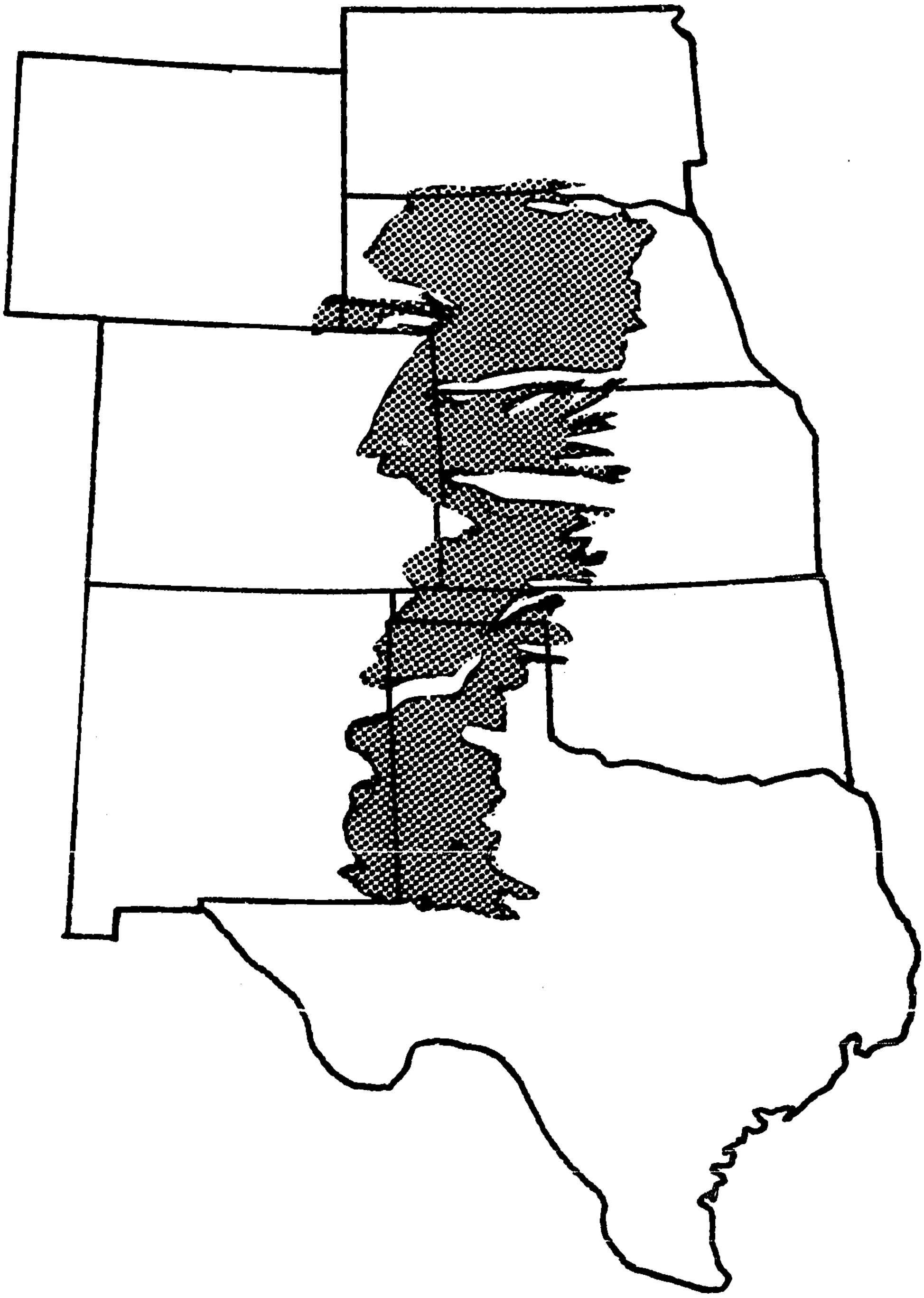

Figure 1.2. The Ogallala Aquifer (adapted from Sloggett, 1977)

from the mountains where it originated and reduced the formation along its eastern border. The Ogallala Formation outcrops in places but is mostly overlain with alluvial or Aeolian deposits of Pleistocene and Holocene epochs.

The water in the Ogallala Aquifer has accumulated gradually over thousands of years. A few rivers may contribute to the aquifer at least part of the year, but the main source of water to the aquifer is rainfall. The recharge from rainfall is less than an inch per year.[1] In places, the equivalent of more than 100 feet of water can presently be found. But the thickness of the saturated material and, therefore, the amount of water under a specific area shows considerable variation because of undulations in the surface of the underlying formations. The underlying formations themselves are quite impervious and, therefore, have limited or local significance for irrigation.

The water table throughout most of the area lies in the Ogallala Formation, but in eastern Nebraska, it lies well above the Ogallala Formation in more recent strata. The water in these formations are technically distinct aquifers but are treated as part of the Ogallala Aquifer in this study because they are hydrologically connected. Because of variations in surface topography, including relief and patterns of discharge and recharge to the aquifer, the depth to water also shows considerable variation throughout the Ogallala Aquifer.

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[1]Numerous authors have estimated that less than an inch per year of rainfall recharges the aquifer; see, for example, Lappala (1978) working in Nebraska, Jenkins and Pabst (1975) in Kansas, and Wyatt, Bell, and Morrison (1977) in Texas.

1.2. Economic Development of the Aquifer

The widespread adoption of irrigation with water derived from the Ogallala Aquifer first occurred during the 1940's and 50's in Texas and New Mexico south of the Canadian River in the Southern High Plains. According to the Bureau of Reclamation, Region Five (1968), there were 600 irrigation wells in this area in 1937 and around 44,000 by 1958. In contrast, a nine-county area in northwest Kansas had only about 100 wells in 1950, but the number increased to 2,200 by 1972 (Jenkins and Pabst, 1975); there were 383 applications for new wells in the same area in 1977 (Kansas State Board of Agriculture, 1978).

To further illustrate the pattern of development, the counties indicated in Figure 1.3 are denoted as part of an "Ogallala Zone." The aquifer also stretches into some counties adjoining this area, but the area indicated covers nearly all of the area where the Ogallala is the main source of groundwater and irrigation is significant economically.[1] The area does not include sections where discontinuous fragments of the Ogallala Aquifer have been identified, such as central Kansas and southeastern Colorado and Wyoming. The area indicated in Figure 1.3 defines the areas assumed to use water from the Ogallala Aquifer in the rest of the study. It is divided into three subsections for the purposes of presenting data which I call the North, Central, and South Ogallala zones.

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[1]The area in eastern Nebraska is not included even though an important area of irrigation. The hydrology of this area was too complicated and the data so poor that this area was excluded even though groundwater mining is an important concern here.

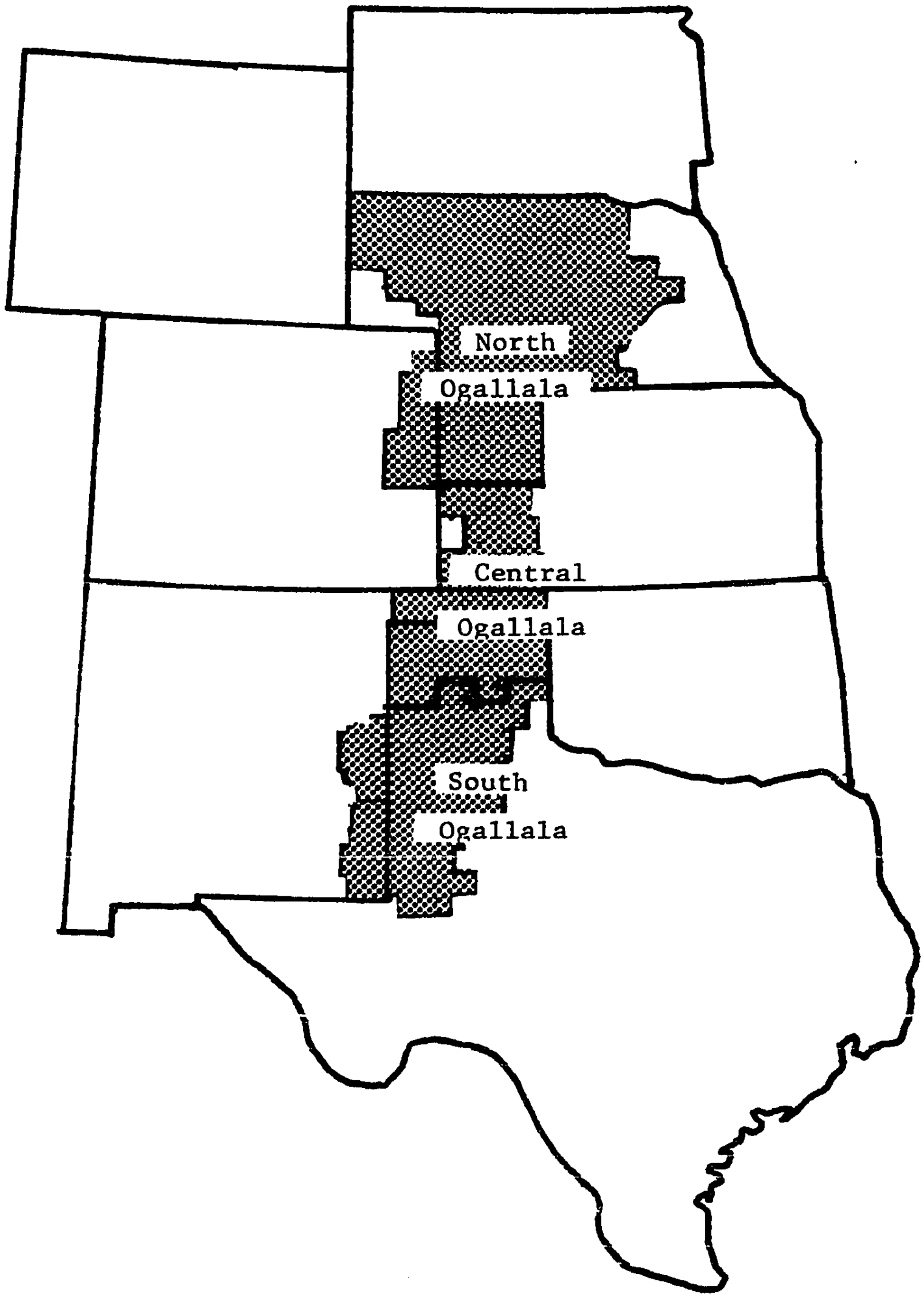

Figure 1.3. Area assumed to use the Ogallala Aquifer in this study

The area irrigated in the South Ogallala Zone, which basically corresponds to the Southern High Plains of Texas and New Mexico, is about the same in 1974 as it was in 1959, as shown in Figure 1.4. But a continued expansion of the area irrigated has occurred in this time period in the Central and North Ogallala zones. Refer to Table 1.1 for the actual number of acres irrigated. The data include area irrigated with water from all sources including groundwater and surface water from originating on farm and from irrigation organizations. Groundwater from the Ogallala would account for around 80, 98, and 100 percent of the area irrigated in the North, Central, and South Ogallala zones, respectively, in 1969. The entire Ogallala Area accounts for

Table 1.1. Historical development of irrigation from the Ogallala Aquifer[a] in comparison with national trends[b]

Area	Year			
	1959	1964	1969	1974
	(1,000 acres)			
North Ogallala	1,317	1,457	1,992	3,061
Central Ogallala	865	1,337	2,189	2,437
South Ogallala	3,811	3,987	3,933	3,877
Total Ogallala	5,993	6,781	8,114	9,375
Total United States	33,163	37,056	38,196	41,243

[a]Data include all irrigation in the regions including groundwater from all sources, privately and publically provided surface water. Groundwater from the Ogallala Aquifer would irrigate around 80%, 98%, and 100% of the acres shown for the North, Central, and South Ogallala zones, respectively, in 1969.

[b]Source: Department of Commerce (1961, 1967, 1972, 1977).

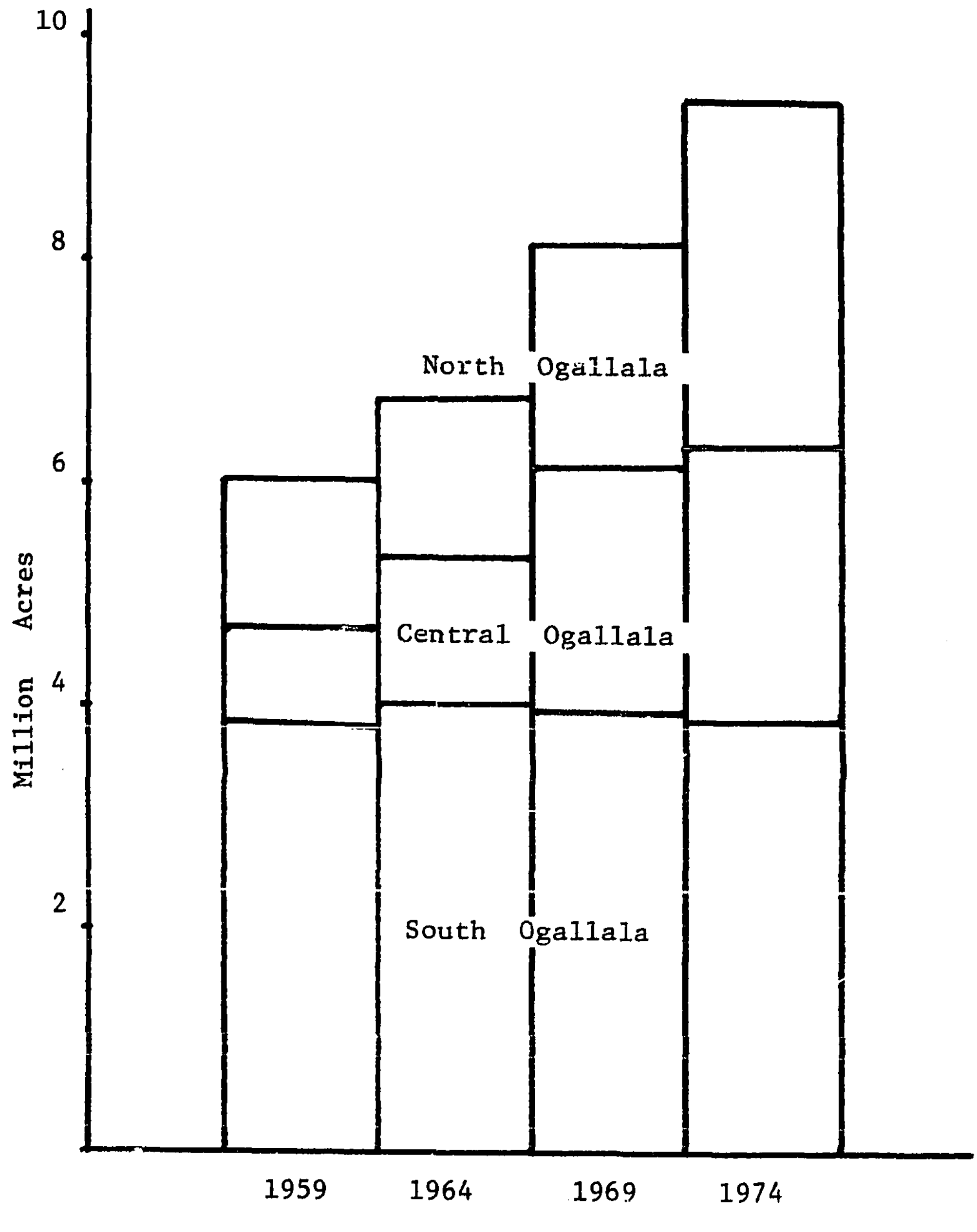

Figure 1.4. Growth of area irrigated in the region drawing upon the Ogallala Aquifer, 1959-74

nearly 42 percent of the increase in the area irrigated between 1959 and 1974 and nearly a fourth of the entire area irrigated in the United States.

Different crops are important in different parts of the Ogallala Zone. In the North Ogallala Zone, 77 percent of the area irrigated in 1974 was used to produce corn, while hay, the next most important irrigated crop, accounts for 9 percent of the area irrigated. In the Central Ogallala Zone, the irrigated area is almost evenly divided between corn, wheat, and sorghum at 32, 32, and 26 percent, respectively. Cotton and sorghum are most important in the South Ogallala Zone, with 37 and 27 percent of the irrigated area; wheat and corn account for an additional 13 and 11 percent, respectively.

Irrigation is important in the area in many different ways. As shown in Figure 1.5, its significance in terms of land use is much greater in the South Ogallala Zone than in the North and Central Ogallala zones. Comparisons of the area irrigated with the total area harvested understate the importance of irrigation, because yields per acre are higher and more inputs per acre are used on irrigated land. Agribusiness firms and services in general have benefited from the increased demand for their products resulting from expanding irrigation. Local employment and income multipliers for each extra dollar of farm income resulting from irrigation have been estimated to be about 2.00 and 2.05 (Osborn, 1973).

North Ogallala:

Central Ogallala:

South Ogallala:

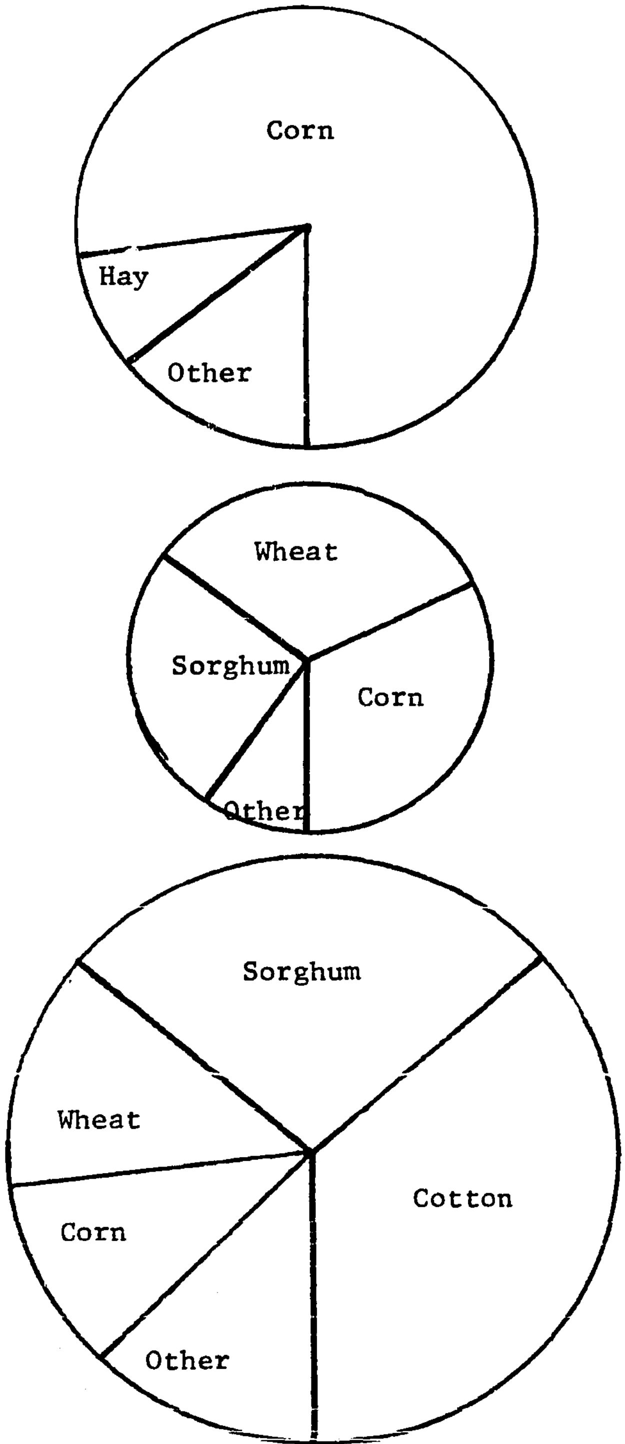

Figure 1.5. Irrigated area by crop in the region drawing upon the Ogallala Aquifer in 1974

1.3. The Impact of a Falling Water Table and Rising Energy Prices

Energy costs are a concern to all farmers but perhaps especially so to those who irrigate with groundwater. Pumped water has to be lifted the vertical distance between the discharge point in the field and the surface of the pumped well. The action of pumping a well creates a "cone of depression" in the water table around the well; the drawdown of the water level in the well is a component of pumping lift. If the water table drops by a foot, then lift increases by a foot *ceteris paribus*. But all things are not necessarily equal. As the thickness of the saturated material thins, well performance decreases, causing the drawdown and, therefore, the pumping lift to increase for a given well yield. Assume an energy conversion efficiency of 22 percent, a pump efficiency of 60 percent, and 24 inches of water applied per acre per year; an additional 0.2 gallons per year of diesel would then be required for each additional foot of pumping lift. Annual rates of decline of the water table of nearly four feet per year have been recorded in parts of the Southern High Plains of Texas. Rates of decline of one foot per year or better have been recorded in most counties in Kansas, Colorado, and Nebraska. The effect of the decline is, of course, cumulative.

Eventually, additional capital costs also have to be incurred to deepen existing wells, install longer pumping units, or even drill additional wells to irrigate an area formerly irrigated by a single well. The end process is one in which the costs of irrigation or poor well performance because of the thinness of the saturated material force the irrigator to revert to dryland production.

Energy prices are an important component of the total costs of irrigation, and energy prices have been rising rapidly since the Arab-Israeli War of October 1973. Indices of energy prices as well as the prices of all agricultural inputs are shown in Table 1.2 with 1967 as the base year. An approximation of the prices of energy relative to other agricultural input prices is shown in Table 1.3.[1] Energy prices fell relative to the prices of other farm inputs between 1967-72, encouraging energy intensive production methods such as irrigation. But prices rose rapidly during the period 1973-74, with diesel prices nearly doubling. During the period 1975-79, relative energy prices except for natural gas were fairly stable. Natural gas prices continued to rise, largely because they were underpriced at the beginning of the period because of regulation. The regulations have been slowly retracted, and natural gas prices should be completely deregulated by 1985. The beginnings of the current round of price rises which originated with cutbacks in Iranian production are evident in the last two observations. It seems likely that another doubling of the relative price of energy will occur by 1990: the data in Table 1.2 demonstrate that relative energy prices virtually doubled between 1975 and 1980 despite legislative protection.

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[1]This is an approximate index, because energy prices are included in the price of all agricultural inputs. As such, the index baffles the shift in the price of energy relative to other agricultural inputs.

Table 1.2. Historical trends in indices of energy prices and farm inputs 1972-79.

Year	Quarter[b]	All Farm Inputs[c]		Energy[a] Diesel		Energy[a] Natural Gas		Energy[a] LPG[d]		Energy[a] Electricity	
Base Year		1967	1975	1967	1975	1967	1975	1967	1975	1967	1975
1972	1	125	68	101.9	40.9	117.6	54.6	91.3	41.3	117.2	66.8
	2	128	69	101.9	40.9	120.2	55.8	91.3	41.3	118.8	67.7
	3	129	70	101.9	40.9	122.8	57.0	98.6	44.6	120.2	68.5
	4	134	71	101.9	40.9	126.2	58.6	98.6	44.6	119.9	68.4
1973	1	142	77	101.2	40.6	125.8	58.4	98.6	44.6	123.2	70.2
	2	152	81	110.3	44.3	130.1	60.4	121.8	55.1	125.4	71.5
	3	155	83	117.3	47.1	135.8	63.1	121.8	55.1	127.4	72.7
	4	158	83	136.8	54.9	141.5	65.7	126.1	57.1	130.9	74.6
1974	1	166	88	198.8	79.6	147.8	68.6	150.8	68.2	143.1	81.6
	2	170	89	230.3	92.5	151.7	70.5	150.8	68.2	154.2	87.9
	3	181	94	247.4	99.3	159.8	74.2	187.0	84.6	161.3	92.0
	4	185	95	239.1	96.0	175.8	81.4	182.6	82.6	164.0	93.5
1975	1	179	96	235.4	94.5	190.0	88.2	182.6	82.6	172.5	98.3
	2	190	100	243.8	97.9	219.7	102.0	220.9	100.0	173.5	98.9
	3	192	103	258.0	103.6	229.4	106.5	237.8	107.6	179.6	102.4
	4	190	102	271.4	109.6	239.5	111.2	263.9	119.4	178.1	101.5

[a] Source: Department of Labor (1974-78 and 1979).
[b] Price indices are for last month in quarter.
[c] Source: Department of Agriculture (1972-78 and 1979).
[d] Liquid Petroleum Gas.

Table 1.2. (continued)

Year	Quarter[b]	All Farm Inputs[c]		Energy[a] Diesel		Natural Gas		LPG[d]		Electricity	
Base Year		1967	1975	1967	1975	1967	1975	1967	1975	1967	1975
1976	1	199	106	270.7	108.7	248.5	115.4	272.5	123.3	180.7	103.0
	2	201	107	267.2	107.2	279.0	129.6	289.9	131.2	185.6	105.8
	3	200	107	275.1	110.4	294.3	136.7	291.2	131.8	193.1	110.1
	4	199	107	281.6	113.0	360.6	167.5	310.6	140.5	189.1	107.8
1977	1	209	112	301.2	120.9	370.9	172.3	346.9	157.0	197.2	112.4
	2	210	113	309.7	124.3	386.6	179.6	359.9	162.9	210.5	120.0
	3	206	112	311.4	125.0	405.2	188.2	373.3	168.9	217.5	124.0
	4	207	113	314.4	126.2	454.0	210.9	383.1	173.3	210.1	119.8
1978	1	222	119	314.5	126.3	469.6	215.8	368.9	166.9	219.2	125.0
	2	228	122	313.7	125.9	480.0	226.7	342.2	154.8	225.0	128.3
	3	229	124	314.7	126.3	504.6	234.4	324.0	146.6	223.8	127.6
	4	233	126	328.5	131.9	529.8	246.1	317.6	143.7	218.7	124.7
1979	1	255	135	353.7	142.0	575.2	267.2	313.6	141.9	222.1	126.1
	2	259	138	428.7	172.1	629.6	292.4	352.9	159.7	236.6	134.9
	3	254	135	543.7	218.2	684.1	317.6	478.6	216.5	245.5	139.9
	4	259	138	575.5	231.0	746.2	346.5	566.1	256.1	245.1	139.7

Table 1.3. Indices of energy prices relative to all farm inputs, 1972-79

Year	Quarter	Diesel 1967	Diesel 1975	Natural gas 1967	Natural gas 1975	LPG 1967	LPG 1975	Electric 1967	Electric 1975
1972	1	74.1	55.6	94.1	81.8	73.0	61.8	93.8	100.0
	2	72.3	54.3	93.9	81.6	71.3	60.3	92.8	98.9
	3	71.8	53.9	95.2	82.7	76.4	64.6	93.2	99.4
	4	69.1	51.9	94.2	81.8	73.6	62.3	89.5	95.4
1973	1	71.3	53.5	88.6	77.0	69.4	58.7	86.8	92.5
	2	72.6	54.5	85.6	74.4	80.1	67.8	82.5	88.0
	3	75.7	56.8	87.6	76.1	78.6	66.5	82.3	87.7
	4	86.6	65.0	89.6	77.8	79.8	67.5	82.8	88.3
1974	1	119.4	89.6	89.0	77.3	90.8	76.8	81.2	91.9
	2	135.5	101.7	89.2	77.5	88.7	75.0	90.7	96.1
	3	136.7	102.6	88.3	76.7	103.3	87.4	89.1	95.0
	4	129.2	97.0	94.8	82.4	98.7	83.5	88.6	94.5
1975	1	131.5	98.7	106.1	92.2	102.0	86.3	96.4	102.8
	2	128.3	96.3	115.6	100.4	116.3	78.4	91.3	97.3
	3	134.4	100.9	119.5	103.8	123.9	104.8	93.5	99.7
	4	142.8	107.2	126.1	109.6	138.9	117.5	93.7	79.9
1976	1	136.0	102.1	124.9	108.5	136.9	115.8	90.8	96.8
	2	132.8	99.7	138.8	120.6	144.2	122.0	92.3	98.4
	3	137.6	103.3	147.2	127.9	145.2	123.2	96.6	103.0
	4	141.5	106.2	181.2	157.4	156.1	132.1	95.0	101.3
1977	1	144.1	108.2	177.5	154.2	166.0	140.4	94.4	100.6
	2	147.5	110.7	184.1	159.9	171.4	145.0	100.2	106.8
	3	151.2	113.5	196.7	170.9	181.2	153.3	105.6	112.6
	4	151.9	114.0	219.3	190.5	185.1	156.6	101.5	108.2
1978	1	141.7	106.4	209.3	181.8	166.2	140.6	98.7	105.2
	2	137.6	103.3	214.0	185.9	150.1	127.0	98.7	105.2
	3	137.4	103.2	220.3	191.4	141.5	119.7	97.7	104.2
	4	141.0	105.9	227.4	197.6	136.3	115.3	93.9	100.1
1979	1	138.7	104.1	224.6	196.0	123.0	104.1	87.1	92.9
	2	165.5	124.2	243.1	211.2	136.3	115.3	91.4	97.4
	3	214.1	166.7	269.3	234.0	188.4	159.4	96.7	103.1
	4	222.2	166.8	288.1	250.3	218.6	184.9	94.6	100.9

The future course of energy prices is subject to great uncertainty. It seems likely that prices will increase at least until the end of the century. The experience of the past is that the energy price increases come suddenly, originating in political changes in the oil producing states. Increased energy prices will accelerate the economic exhaustion of the Ogallala Aquifer and shorten the time period when the region has to adjust to reduced agricultural production.

1.4. Purpose, Scope, and Methodology

The prospects for agricultural production with a declining water table in the Ogallala Zone have sparked interest in methods to prolong the useful life of the aquifer and a search for alternative sources for water. Groundwater conservation districts have been formed in three of the states. The districts promote awareness of the problem, increased efficiency in water use, and promulgate regulations to limit well-interference, and in Nebraska, limit withdrawals. A large number of independent studies have been done, especially in Texas, projecting the amount of land irrigated and assessing impacts of declining irrigation on other sectors for subsections of the entire Ogallala Zone. More recent studies have incorporated changing energy prices (Coomer, 1978; Young, 1977; Mapp and Dobbins, 1977). The Bureau of Reclamation has completed two studies investigating the possibilities of importing water into the region; the first was a reconnaissance study (Department of Interior, Region Five, 1968), and the second, a detailed evaluation of importing water from the Mississippi Delta, the most promising route found in the reconnaissance study. The benefit cost ratio determined in the latter study was 0.27 (Department of Interior, 1973). Another large study is currently being undertaken for the Economic Development Administration by Camp Dresser and McKee, Inc., Black and Veatch, and Arthur D. Little, Inc., which are collectively called the High Plains Associates. The purpose of their study (High Plains Associates, 1979) is to evaluate other interbasin transfers and a wide range of issues that arise out of the declining water table in the Ogallala Aquifer.

The purpose of the present study is related to all of the above but somewhat differently. The objective is to evaluate the future competitive viability of irrigation in the Ogallala Zone. The study focuses on the specific years 1990 and 2000 in an interregional model of competitive equilibrium national in scope. The relative impacts on irrigation in the Ogallala Zone of the falling water table, rising energy prices, and changing levels of demand are assessed.

A regional, recursive, linear programming model is used to determine competitive advantage. A mathematical description of the range of irrigation of production possibilities and constraints from the Ogallala Aquifer is incorporated into a revised version of the CARD[1] energy model. The variation in production possibilities includes combinations of four depths to water intervals and two saturated thickness intervals, each with different cost and energy requirements. Existing rates of decline of the water table and the historical configuration of the aquifer are used to project the range and extent of irrigation possibilities for 1990. The recursive element is introduced in the model in that withdrawals as determined by the solution to the 1990 model are used, in part, to determine the rate of decline for the period 1990-2000.

A total of five solutions are examined. The solutions encompass three levels of demand and two sets of energy prices. The effect of

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[1]Center for Agricultural and Rural Development.

changing demands and energy prices is evaluated through a comparison of model solutions. The effect of the falling water table is evaluated by a comparison of the solution with what the solution would be if the water table had not declined under ceteris paribus assumptions.

The rest of the dissertation is divided into four main parts. Chapter 3 contains a review of background information that influenced, in part, the structure of the linear programming model. This part includes subsections on other studies of the Ogallala Aquifer, the legal basis for water rights, especially groundwater in the Ogallala Zone, and the relevant economic theories which justify decision processes within the linear programming model. Chapter 3 contains a description of model's activities and constraints, especially production possibilities and constraints from the Ogallala Aquifer. Results are presented in Chapter 4. Chapter 5 contains a summary, a discussion of model limitations, and conclusions.

2. FRAMES OF REFERENCE

There are a number of perspectives from disparate areas of research that have contributed to the formulation of the objectives and the way the objectives are resolved in this study. These perspectives are brought together and summarized in this chapter.

2.1. Previous Studies of the Ogallala Aquifer

2.1.1. Hydrologic studies

The earliest studies of the Ogallala Formation were conducted by geologists and hydrologists in the latter part of the 19th century. The early studies dealt with the general geology of the area, and some authors also described such things as the occurrence of groundwater, depth to the water table, and water quality. Over time these studies have become more detailed because of the accumulation of knowledge about the formation, growth of data available from the increase in number of irrigation and observation wells, and expansion of theoretical and technological techniques in the science of hydrology.

By the late 1960's, most of the area of the Ogallala had been studied at some time. Most of the hydrological data on the Ogallala Aquifer, however, are contained in county, basin, or studies of surface formations. There have been some attempts to synthesize these data into a more general picture of larger sections of the aquifer. McGuinness (1964) produced his groundwater map of the United States which shows the areal extent of the Ogallala Aquifer. Cronin (1969) was able to produce a map of the Southern Ogallala showing contours of the water table and saturated thickness. This type of data is not uniformly available for the Central and Northern sections of the Ogallala. Such data as are available remain scattered among a great many publications.

Most of the work in Nebraska have been basin studies covering parts or all of several counties and are published as Water Supply Papers of the United States Geological Survey (USGS). Maps of saturated thickness and depth to water are not generally included. The problem is complicated in Nebraska by the overlapping of saturated materials in several geologic formations and the water table being considerably above the Ogallala Formation. Some recent maps of individual counties have been published as Hydrological Atlases. A USGS Water Supply Paper by Boetcher (1966) covers the Northern High Plains in Colorado with maps of depth to water, saturated thickness, estimates of recharge and discharge, and results of well tests. There are a series of county studies in Kansas in the 1940's and 50's covering all of the counties over the Ogallala Formation. These are published as Water Supply Papers of the Kansas Geological Survey. Some Hydrological Atlases have been published more recently that deal with the Northern Ogallala Formation in Kansas. A study of the Central Ogallala in southern Kansas encompassing 12 counties is still in preparation. Hydrological Atlases have been published mapping the Ogallala in the panhandle area of Oklahoma. The Department of Water Resources in Texas is in the process of publishing county maps of the Ogallala giving pumping lift, saturated thickness, and well yield. In addition, maps have been produced by groundwater conservation districts in Texas. The only comparable data for New Mexico are in the report by Cronin referred to above.

The hydrologic studies used directly in this study are given in Appendix A, Table A.1. In addition, theoretical material by the Department of Interior (1977), Edward E. Johnson, Inc. (1966), and Muller and Price (1979) proved useful.

2.1.2. Representative farm studies

Among the earliest economic studies was a representative farm study done by Hughes and Harman (1969) encompassing all or parts of 21 counties in the Southern Ogallala region (Southern High Plains) of Texas. Hughes and Harmon used a recursive linear programming (LP) model to study 80 resource situations over the period 1966-2015 inclusive. In aggregate, their study included four soil and climate categories, five depths to water categories, and ten saturated thickness categories. The 80 resource situations were a subset of the permutations of the soil and climate, depths to water, and saturated thickness categories. For each resource situation, the LP was solved on an annual basis and the solution used to modify the LP to be solved for the following year; most notably, the coefficients reflecting well yield, pump lift, and irrigation costs were changed. The procedure was iterated until the representative farm reverted to dryland farming or for the full 50 years. The results aggregated over the region gave a gradual decline, during the entire period, of acre feet of water used, acres irrigated, and of gross and net farm income. The number of irrigated acres declined by 96 percent over the entire period of the study, with 69 percent of the decline occurring before 1990. Production of major crops such as cotton and sorghum was projected to decline by 65 and 90 percent, offset somewhat by a 22 percent increase in wheat production. Gross and net farm returns were projected to decrease by 41 and 48 percent, respectively, by 1985 and 70 and 69 percent over the entire time period.

Mapp and Eidman (1976) used a representative farm approach in the Central Ogallala region. Their primary concern was to evaluate the effect of alternative policies limiting groundwater use. The three policies they examined are no controls, limited pumping in each year, and a graduated tax on the amount of water pumped. They used a 640-acre representative farm in a good water resource situation (i.e., 325-foot initial saturated thickness) and a poor water resource situation (i.e., 100-foot initial saturated thickness). Mapp and Eidman constructed a growth simulator for the major crops grown on the representative farms to quantify the effects of moisture stress on farm yields. A simulation model of the representative farms was used to predict management decisions over a 20-year period. The tax policy proved definitely superior to the policy of direct regulation, because it allowed more flexibility in adjusting pumping to the needs of the crop. Policy had little effect on the trend in water use over the 20-year simulation period but did affect the quantities. Farm income and amount of irrigation water applied was maintained for only the first ten years and then declined steadily for the farm in the poor resource situation. The farm in the good resource situation showed stable amounts of irrigation water applied and a gradually increasing farm income throughout the period.

Mapp and Dobbins (1977) used a static and recursive LP model in a representative farm study in the Oklahoma panhandle. Nine representative farm situations were analyzed consisting of three water resource situations and three farm sizes. A prime concern in this study was the interaction of increasing energy prices with cultivation practices and water use. Twenty-four crop production alternatives were included in the static model which was used to evaluate short-run impacts of higher energy prices. Long-term effects were evaluated with the recursive LP model. Ten solutions for a sequence of five-year periods were obtained.

Mapp and Dobbins examined three price scenarios consisting of both high and low agricultural prices with constant natural gas prices and rising natural gas prices with constant crop prices at the high level. Irrigation water use fell off in all scenarios, dropping immediately in the poor water situation and after a log of 20-30 years in the other two water situations. Net farm incomes also declined continuously in all cases. The effect of the rising natural gas prices was to make the declines more precipitous and to a lower level and to decrease the economic life of the aquifer by about ten years.

Several studies of irrigation in the High Plains of Texas have been completed at Texas A & M University. The representative farm approach has been adopted in many of these studies. Condra, Lacewell, Sprott, and Adams (1975) used a linear programming model of a representative farm to estimate normative demand curves for water. This line of analysis was extended to evaluate the effect of changing input and product prices on the demand for water by Lacewell, Condra et al (1978).

The demand curves are derived by parametrically increasing water costs, but these studies do not deal with the interaction of water use and rising costs because of depleted groundwater supplies.

The interaction is analyzed explicitly by Lacewell, Condra, et al. (1978). One model reported in this study is a recursive LP of a 640-acre representative farm in the Texas High Plains. Three water resource situations were modeled; good, fair, and poor, defined more rigorously as 250, 125, and 75 feet of saturated thickness, and 250, 175, and 75 feet of pump lift, respectively. Three natural gas price scenarios were examined which consisted of a constant natural gas price of $1.50 per thousand cubic feet and arithmetically increasing prices at annual rates of $0.10 and $0.25 per thousand cubic feet. The representative farm is analyzed with both a furrow and center pivot sprinkler distribution system. Thus, a total of 18 variations of the representative farm was encompassed. The representative farm reverted to dryland farming in all but the three most favorable situations in the 25-year period of analysis. In the least favorable situation, the farm reverted to dryland farming in eight years. An interesting facit of the results was that farms in the poor water situation (and smaller pump lifts) continued to operate after farms in the good and fair water situations reverted to dryland farming with the high rate of increasing natural gas prices.

2.1.3. Regional programming studies

A regional programming study covering 32 counties of the Texas High Plains was recently completed by Coomer (1978) and Young (1977).

The study area was divided into five regions with distinct soils, crops, and irrigation methods assumed in each region. The land in each region was divided into six categories according to the saturated thickness of the aquifer. A recursive linear programming model was solved for the five-year periods 1976-2025. Upper bounds on crop production for each time period were determined from historic trends. The model was solved for three levels of grain prices and with both 1976 natural gas prices and geometrically increasing natural gas prices. The results of Coomer and Young's study showed an immediate decline in acres irrigated, irrigation water applied, and in production of most major crops (except wheat). Increased natural gas prices greatly accelerated the economic exhaustion of the aquifer.

Bekure (1971) used a recursive linear programming model in a meticulous study of the entire Central Ogallala Aquifer. Bekure's model incorporated six saturated thickness classes, eight depths to water, two soil classes, and two land management classes, for a total of 196 resource situations. The amount of land available in each class was determined from maps. He solved his model for the 20 five-year periods 1965-70 to 2065-70. The model maximized returns subject to upper bounds upon production by crop. Two sets of upper bounds were used, both allowing production to increase at different rates above 1965 regional production. Bekure's results projected irrigated acres and water applied to increase during the period 1965-99. The number of irrigated acres during the peak period 1990-99 varies, however, between 1.63 and 3.4 million acres according to the upper bounds placed upon production. After 1999, irrigated acres decline steadily and, in the case where 3.4 million acres are irrigated during 1990-99, precipitously. Production of major crops follows this trend. Some of the 196 water resource situations revert to dryland farming as early as 1980 in one solution.

Bekure's aggregate results are in sharp contrast to the aggregate results obtained by Hughes and Harman, and Young and Coomer in that an initial increase in irrigation is projected rather than a continuous decline. Bekure's results probably stem from the fact that he was modeling the Central Ogallala rather than the Southern Ogallala, which experienced widespread adoption of irrigation earlier. This suggests that the course of development of the Ogallala may involve the gradual immediate decline of irrigated agriculture and production in the Southern Ogallala and expansion in the Central and Northern Ogallala. This shift northwards of irrigation and production was in fact assumed by Osborn (1973) in an input-output study of the High Plains of Texas. This hypothesis also appears to be supported by the evidence of the last two decades. According to the State of Kansas' Governor's Task Force on water resources (1977), irrigated acreage has nearly tripled during the period 1965-67 to 1977 in Kansas. Compare this with the 15 counties in High Plains Underground Water Conservation District No. 1 in the Southern High Plains of Texas, which in 1977 reported the smallest number of permits to drill wells since 1953.

2.1.4. Input-output studies

Input-output studies have been undertaken in Colorado, Kansas, Oklahoma, New Mexico, and Texas to measure the effect of irrigation on local economies. The most detailed and extensive studies have been undertaken in Texas, stemming from data gathered for the Texas Input-Output Model. The Planning Agency Council for Texas initiated, in 1968, a state-wide survey to develop data for input-output models. Region 2 is the Texas High Plains where Dr. James Osborn directed research.

The initial study, documented by Osborn and McCray (1972), found that agriculture accounted for 15.4 percent of the value of 1967 output and 23.3 percent of employment in the region. The average direct and indirect benefits (expenditures) per dollar of net increase in the value of crop production was estimated to be $2.79. In 1973, Osborn estimated that total economic activity would decline by 400 million dollars, income would decline by 110 million dollars, and employment would decline by nearly 17,000 jobs between 1980 and 1990 because of the decline of the water table. These estimates are based upon $63.90 of direct benefits to the farmer per acre irrigated rather than farmed without irrigation, and $3.30 of additional benefits in the region for each dollar of direct benefits to the farmer. Type II income and employment multipliers both equal 1.84. Osborn uses the projection by Grubb that irrigated acres would decline by 1.34 million acres in estimating aggregates.

A number of subsequent studies have used the data from Osborn's survey as the basis of their research. Osborn and Harris (1973) examined interindustry effects of the declining groundwater supply in the Southern High Plains of Texas for the period 1967 to 2015 for a 21-county subarea using projections of the amount of land reverting to dryland production from the Hughes and Harmon study described above.

Total benefits from irrigation decreased by 0.9 billion dollars from the 1967 peak of 1.7 billion dollars. The study was expanded to 56 counties by Osborn and Mason (1974) using projections of the irrigated area in the additional 35 counties developed by the Texas Water Development Board. Part of the effect of the decline in irrigated land in the 21-county subarea was offset by increases in irrigation in the Northern High Plains of Texas.

A number of subsequent studies found similar results. A study by Ekholm et al. (1976) and Lacewell, Jones, and Osborn (1976) covered the three western counties of Oklahoma and the 25 northern counties of Texas. These studies combined projections of the area irrigated from Bekure (1971) and Texas Water Development Board and extended Osborn's input-output matrix to the Oklahoma counties with a "location-quotient" technique. Relationships between employment and population were combined with the input-output model into a simulation model of the area.

Lansford et al. (1974) developed a linear programming model of the Southern High Plains of New Mexico, a major component of which is an input-output matrix developed by Osborn and McCray (1967). Lansford compared the effect of alternate arbitrary water availability scenarios on model solution.

Rohdy, Tanner, and Barkley (1971) examined the secondary effects of irrigation on the Colorado High Plains. Kit Carson County was chosen as a county representative of this region. Direct and indirect requirements per dollar of output by sector were determined by examining cancelled checks which had passed through local banks during ten different business days in 1966. The Type II income multiplier for irrigation farming was 2.04 and for dryland farming was 3.08. However, the authors noted that per acre yields are two to five times higher under irrigation farming than dryland farming.

Joe Jack McCullick (1970) did an input-output analysis of four representative counties in southwestern Kansas in order to determine the effects of irrigation on the area's economy. Coefficients for the input-output matrix were obtained from the Kansas input-output matrix, and input requirements for irrigated crops were based on farm budget studies done in eastern Colorado and the Oklahoma panhandle. Type II income multipliers for irrigated crops were relatively low, ranging from 1.53 to 1.95. These low numbers can be partly attributed to the study area's small population, less than 30,000 in 1965. The Type II multiplier for livestock was 4.47. The study estimated that in 1965, 15 percent of the region's personal income could be attributed to the use of irrigated instead of dryland farming.

2.2. Economic Theory

In this section, we review the standard economic concepts which guide the analyses of the declining water table and rising energy prices. Rising energy prices are treated first in section 2.2.1. The next section describes the decision on how much of a resource like water is used. The following sections deal with modifications to the decision rule when a resource stock is involved and the effect of the further complication of commonality.

2.2.1. Interregional competition and resource prices

The effect of a change in the price of a resource used by a competitive industry can be explained in terms of demand and supply curves. A resource such as energy is used in all production processes and all regions in which the industry is located. The effect of increased factor prices is to raise[1] marginal costs and, therefore, ultimately shift the industry supply curve upwards. The effect on industry is to increase the price and decrease quantity at which markets clear, as shown in Figure 2.1.

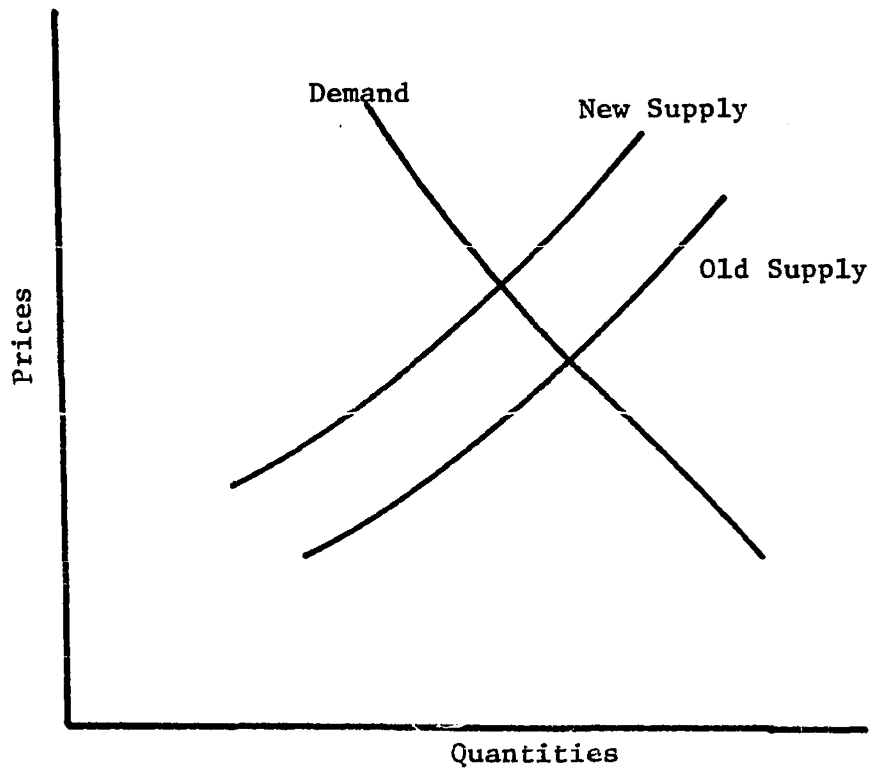

Figure 2.1. Industry effects of an increase in resource costs

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[1]There are extreme situations for which the marginal costs shift down or do not move.

But the individual producer faces infinitely elastic demand curves, because the quantity he produces does not affect price. The marginal cost curve of the individual producer will rise because of the increased factor costs. As a producer, he will see the effect first of all in terms of higher costs, but as the industry adjusts production, the price rises. The beginning and ending equilibrium situations will be something like those shown in Figure 2.2. The beginning and final prices are parameters for the individual producer. He chooses the level of production. The new level of production may be greater than, equal to, or less than the old level of production depending upon whether price or his marginal cost curve shifts more. The value of production may also increase or decrease. The proportion of substitutes used in production will increase, while the proportions of complements decrease. If the individual producers are not identical, then some benefit and some may be damaged in terms of comparative equilibrium positions, although the adjustment process may be difficult for all.

The effects of a resource price rise on a region are directly analogous to the effects on an individual producer. The costs of production in some regions may increase more than in other regions because of an increase in the prices of a resource to an industry. The amount of production in these regions would decrease, while production in other regions may increase. The final position, in a competitive industry, shows no difference in profits, but the regional distribution of production and incomes generated may change in response to shifts in comparative advantage.

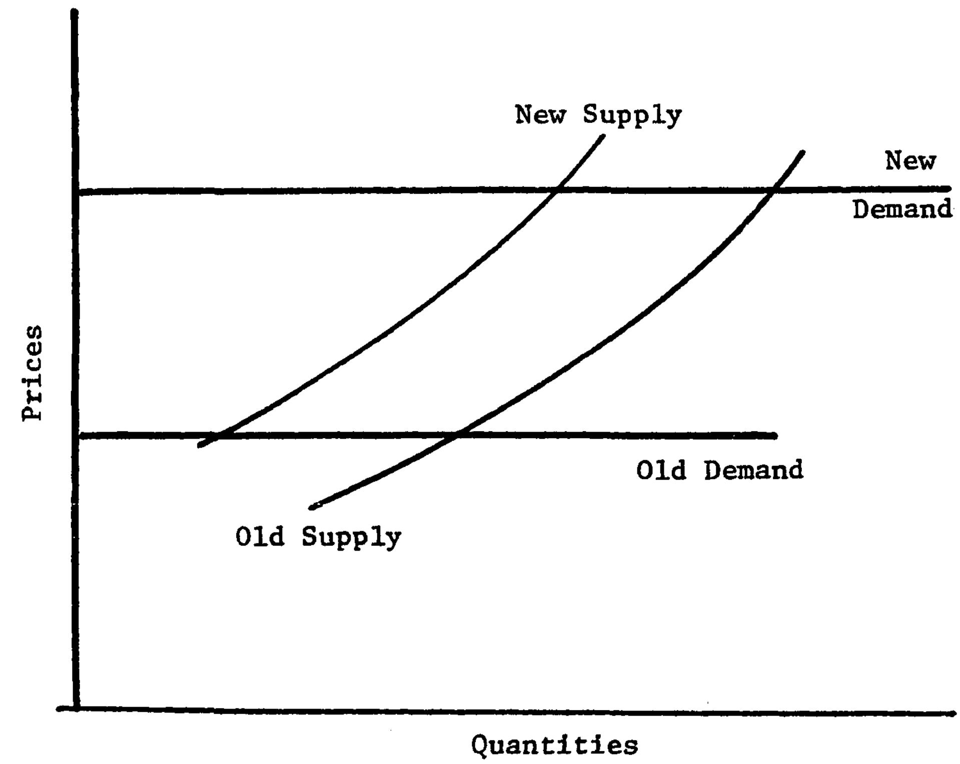

Figure 2.2. Individual producer adjustments to an increase in resource prices

2.2.2. Static selection of the level of resource use

The model presented in this section is the usual rationale of the selection of the level of resource use. It is assumed to hold for most resources, such as energy and water in this dissertation. The argument breaks down where stocks or externalities are involved, both of which are considerations in the mining of a large aquifer. The material is presented so that results may be juxtaposed with the model used to analyze irrigation from such an aquifer in the subsequent section. The example assumed throughout is the level of irrigation water to be applied.

Where water is purchased in a market and the usual maximizing assumptions concerning the irrigator hold, water is applied to the level where the marginal value product of the last acre foot of water equals the cost of the water:

$$MVP_w = P_w. \tag{2.1}$$

Such a situation is applicable if the irrigator is purchasing water from an irrigation organization and has fixed costs in utilizing the water. If costs of using the water are variable, then optimal level of using the water may be described by

$$MVP_w = P_w + MC_{wu}, \tag{2.2}$$

where MC_{wu} is the marginal cost of water utilization.

For using groundwater, the term P_w is zero, and even for surface water, the costs of applying the water is frequently more than the purchase price of the water. In such a situation, the farmer uses the same amount of water every year.

Such a situation would hold for groundwater if recharge rates balanced withdrawals and thus the aquifer was in equilibrium. However, an optimum over time would result from changes in commodity or resource prices. If the irrigator's decisions have no effect on these changes, his decision rule is not affected. For example, if costs rise continuously because of rising energy prices, for example, then the cost of using water may be represented by

$$C = C_o e^{rt}. \tag{2.3}$$

His decision rule is

$$MVP_w(t) = \frac{\partial C_o}{\partial w} e^{rt} = MC(t). \qquad (2.4)$$

Marginal costs rise, as shown in Figure 2.3, and less water is used in every period, but his decision rule is not altered.

A more difficult problem is one in which there are interdependencies between decisions in different time periods. Such a situation arises with groundwater mining, because withdrawals in one period raise

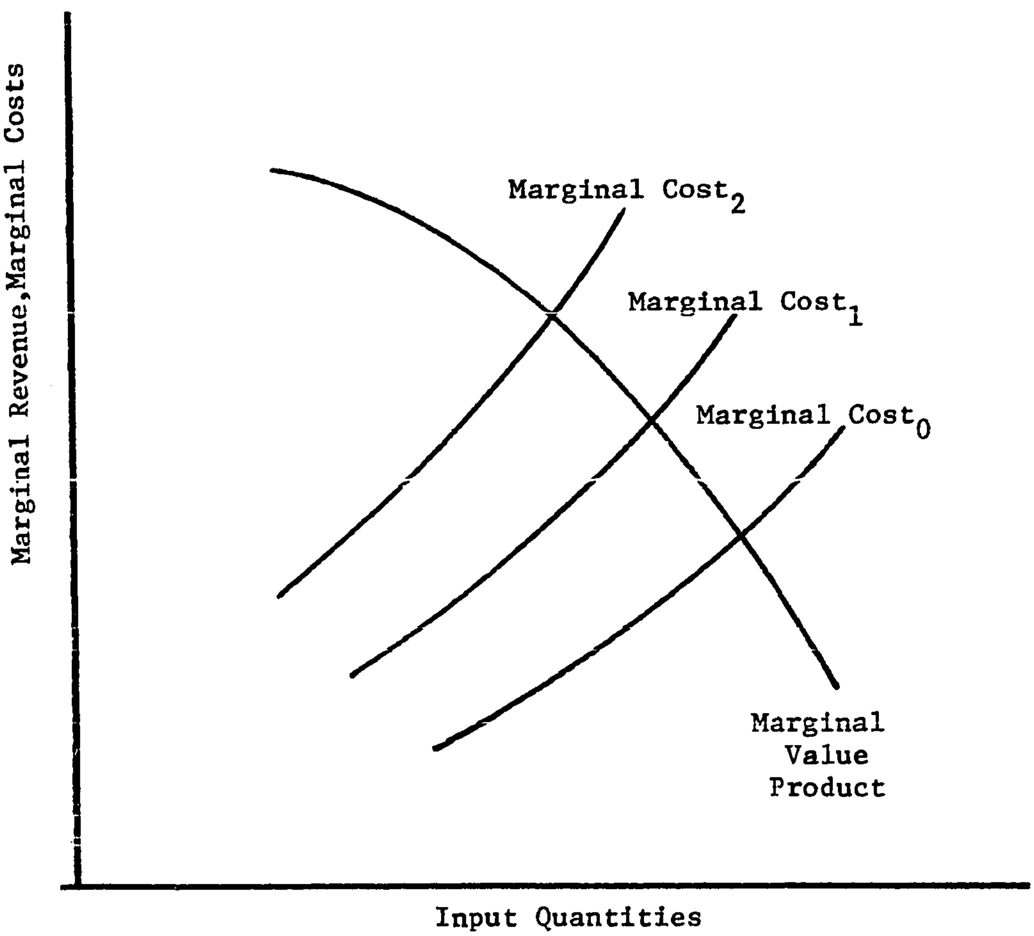

Figure 2.3. Effect of exogenously rising irrigation cost curve

production costs in all subsequent periods by both increasing pumping lifts and decreasing the area that may be irrigated in the future. Static analysis is no longer sufficient to solve such problems.

2.2.3. Dynamic analysis

Optimization over time where there is interdependence between optimum may be analyzed by three alternate methods: calculus of variations, dynamic programming, and the maximum principle. The calculus of variations approach is useful for a particular variant of the control problem. Dynamic programming, first developed by Bellman (1957), is a more general approach, while the most recent method for solving this class of problems uses the maximum principal of control theory.

The general case of the dynamic optimization problem may be written (Intrilligator, 1971) as

$$\max J = \int_{t_o}^{t_1} I(X,W,t)e^{-rt}\, dt + F(X_1,t_1) \qquad (2.5)$$

$$\text{subject to } \frac{dx}{dt} = f(X,W,t)$$

where $I(X,W,t)$ represents intermediate values of the objective function,

$F(X_1,t_1)$ represents the final value of the objective function,

W is the control variable,

X is the stock or state variable,

t is time,

r is the discount rate, and

$f(X,W,t)$ is the equation of motion relating changes in the stock variable to the level of the stock, the control variable, and time.

Equation 5 may also be subject to non-negativity conditions, and initial conditions are assumed known. The solution to the system is a trajectory over time of the control variable and, therefore, of the stock variable so that the objective function value, J, is maximized.

For a problem involving groundwater mining, the objective function would be to maximize the returns I( ) from irrigation over time. The stock, X, is groundwater stored in the aquifer, and the control variable, W, is water withdrawals. The objective is a function of withdrawals both because production (yields, area) depends upon the amount of water applied and irrigation costs are proportional to the amount of water used. Changes in the stock of groundwater influence both the area that can be irrigated and pumping lifts: the greater the volume in storage, the higher the water table and the lower the pumping lifts and costs; the greater the volume in storage, well yields and the areal extent of the aquifer increase enabling the aquifer to support a larger irrigated area.

The rate of change of the stock of water in the aquifer depends directly on net withdrawals for irrigation. Natural recharge and discharge are both dependent upon the stock of water in the aquifer. Springs, for example, dry up as the water table in an aquifer declines, but rivers may switch from being the area's discharge to points of recharge. The change in the stock of water in an aquifer may depend upon time in that periods of abnormal rainfall may also alter levels of natural recharge and discharge. In an aquifer such as the Ogallala, however, the main determinate of the rate of change of the stock of groundwater is withdrawals for irrigation, because the volume of recharge and other discharges are relatively insignificant.

I have not found any empirical application of dynamic analysis to the Ogallala Aquifer in the literature, but Burt, Cummings, and McFarland (1977) used the method to evaluate groundwater mining in the Estancia Valley in New Mexico. They did not estimate the time path of withdrawals and stocks but used an "approximately optimal decision rule" to estimate the final equilibrium stock. The decision rule, shown in Equation 2.6, is derived from Bellman's equation for dynamic programming using a Taylor's series expansion as documented in Burt and Cummings (1977):

$$(r + \frac{\partial f}{\partial x}) \frac{\partial I}{\partial W} = \frac{\partial I}{\partial x} \frac{\partial f}{\partial W} , \qquad (2.6)$$

$$\frac{dx}{dt} = f(X,W) = 0.$$

In the application, I( ), was estimated empirically by regressing data from a number of linear programming solutions, and the equation of motion was assumed to be

$$\frac{\partial x}{\partial t} = 2000 - W = 0, \qquad (2.7)$$

which implies $\frac{\partial f}{\partial w} = -1$ and $\frac{\partial f}{\partial x} = 0$.

The authors are able to solve the system for a number of different steady state levels of groundwater stocks for different discount rates.

2.2.4. The problems of commonality, human and hydrological behavior

An analysis such as that made by Burt, Cummings, and McFarland (1977) can be applied to a region as a whole. But the decisions regarding groundwater use from the Ogallala are made by individual irrigators. Because of the fugitive nature of water and the consequent character of the legal structure regulating[1] groundwater rights, they may behave differently from a decision maker dealing with the area as a whole.

When groundwater is pumped from a well, the withdrawal of water causes a cone of depression to form in the water table around the well. The hydrologic gradient in turn causes water to flow towards the well from the surrounding area. The rate of flow of water into the well depends upon the gradient, the area through which the water is passing, and the permeability (ease with which water can pass through) of the aquifer.[2] When pumping stops, the cone of depression dies out slowly. Over long periods of time, the water withdrawn is distributed across the whole aquifer, but over shorter periods of time, only a localized area is affected.

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[1] There is a discussion of groundwater law in Appendix B.

[2] Darcy's Law is a basic departure point for all groundwater hydrology:

$$V = K\,A\,\frac{dx}{dy}\,, \tag{2.8}$$

where V is the volume of water per unit time,
K is the permeability of the aquifer,
A is the area through which the water is transmitted (e.g., the cylindrical surface of a well), and
$\frac{dx}{dy}$ is the gradient of the water table.

An individual irrigator may feel either that he will bear all of the burden of the change in storage because of the water withdrawn from his well or conversely that he can pass all of the burden on to other property owners or, as is most likely, somewhere in between. The two polar cases are examined below using the maximum principal.[1]

First consider the case where all the effects of the withdrawal are borne by the irrigator similar to the assumptions made by Burt and Cummings (1977). Let the revenue function, I, be specified as follows:[2]

$$I(X,w,t) = P_Q Q(w,Z) - c(w,\dot{x}) - P_Z Z \tag{2.9}$$

where P_i is price of i,

$Q(w,Z)$ is a yield function relating production Q with w and Z such that

$$\frac{\partial Q}{\partial w}, \frac{\partial Q}{\partial Z} > 0, \text{ and } \frac{\partial^2 Q}{\partial w^2}, \frac{\partial^2 Q}{\partial Z^2} < 0,$$

w is withdrawals of water,

Z is some other input which is purchased, and

$c(w,x)$ is the cost of pumping groundwater which depends upon the stock on water in that pumping lifts vary with x so that $\frac{\partial c}{\partial x} < 0$ and $\frac{\partial c}{\partial w} > 0$.

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[1]Arrow and Kurz (1970) give a number of variations in economic applications of this methodology.

[2]The analysis leaves out affect on area and deals only with affect on pumping lift. The results are parallel for both cases dealt with independently. Dealing with both simultaneously gives rise to

The Hamiltonian is

$$H = (P_Q Q(w,Z) - c(w,x) - P_Z Z)e^{-rt} + y\ f(w) \qquad (2.10)$$

where r is the discount rate,

$f(w) = \frac{dx}{dt}$ depends only on withdrawals, and

y is the Lagrangian multiplier interpreted as a shadow price.

The necessary conditions for a maximum are:

$$\frac{\partial H}{\partial Z} = P_Q \frac{\partial Q}{\partial Z} - P_Z = 0,$$

$$\frac{\partial H}{\partial w} = (P_Q \frac{\partial Q}{\partial w} - \frac{\partial c}{\partial w})e^{-rt} + y\ \frac{\partial f}{\partial w} = 0,$$

$$- \frac{\partial H}{\partial x} = \frac{\partial c}{\partial x}\ e^{-rt} = \dot{y}, \text{ and} \qquad (2.11)$$

$$\frac{\partial H}{\partial y} = f(w) = \dot{x}.$$

From the necessary conditions we derive

$$P\ \frac{\partial Q}{\partial w} = \frac{\partial c}{\partial w} + \phi\ e^{rt}, \text{ and}$$

$$\frac{\frac{\partial Q}{\partial w}}{\frac{\partial Q}{\partial Z}} = \frac{\frac{\partial c}{\partial w} + \phi\ e^{rt}}{P_Z}\ , \text{ where} \qquad (2.12)$$

$$\phi = -y\ \frac{\dot{x}}{w}\ .$$

The Lagrangian multiplier, y, is the unit value of the water stored in the aquifer. The unit value of the aquifer declines because of withdrawals as shown in Equation 2.11. The term is positive: the shadow price is positive by definition, and $\frac{\dot{x}}{w}$ 0. Therefore marginal cost curve, $\frac{\partial c}{\partial w} + \phi e^{rt}$, shifts upward, as shown in Figure 2.4. The irrigator would use less water and produce less output per acre at (w_1, Q_1), which is the optimal decision for period 1, than at (w_2, Q_2), which is the optimal decision when there is no interaction with groundwater stocks. Also, the curve shifts upwards over time because of the decrease in x.

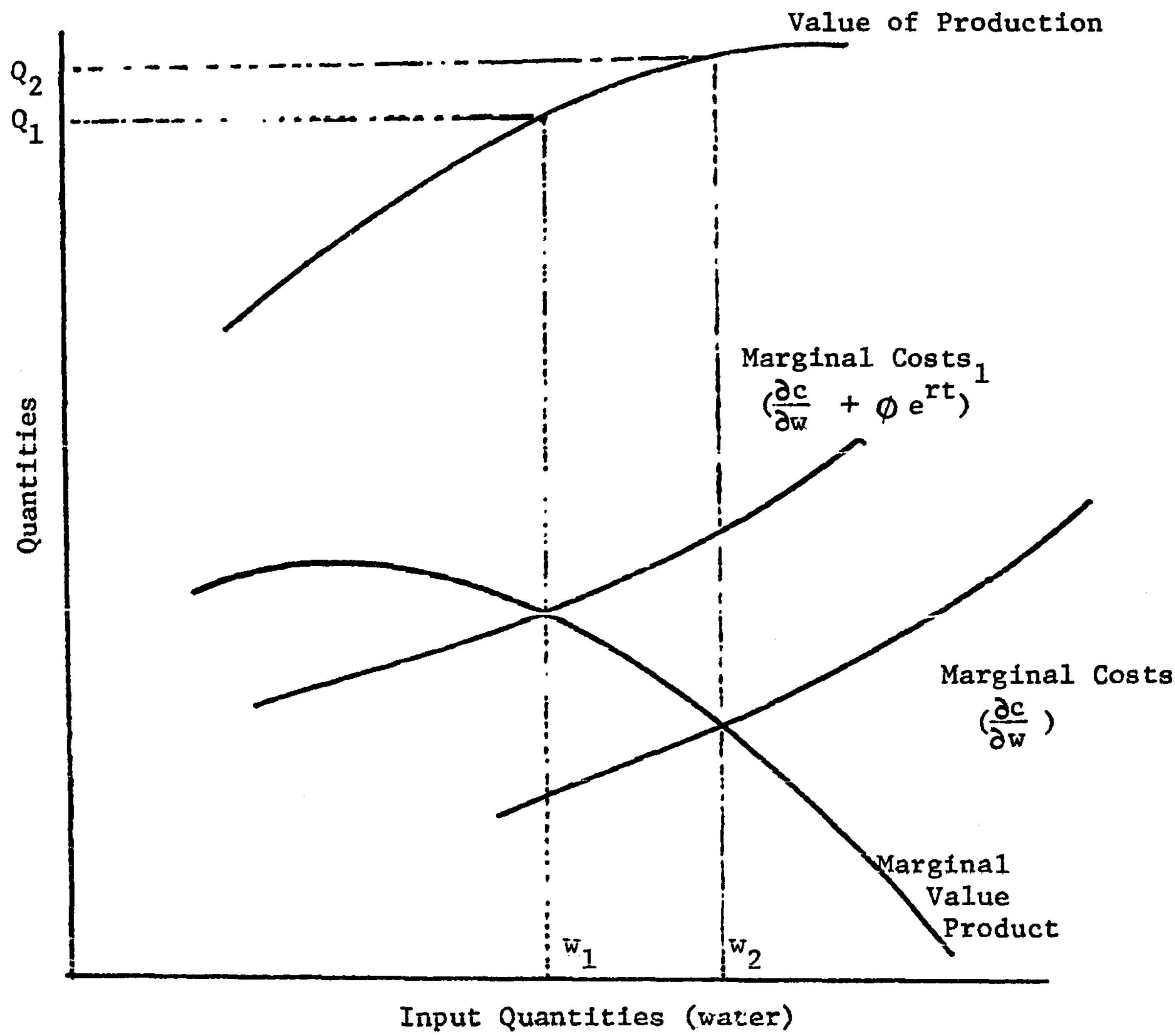

Figure 2.4. Effect of change in water table on water use

The term ϕe^{rt} may be interpreted as the change in the value of the aquifer due to a unit change in withdrawals.

To show the other polar case, we need make only one change in the model. The equation of motion becomes

$$\overset{o}{x} = f(W) \tag{2.13}$$

where $W = a + bw$ = total withdrawals by all irrigators, and

a, b are parameters.

The change in stocks depends on all withdrawals. The decision maker's withdrawals are a marginal contribution to total withdrawals as they are spread out over the entire aquifer. This change introduces the parameter b into Equation 2.14 as follows:

$$\begin{aligned} &P \frac{\partial Q}{\partial w} = c(w,x) + b\phi e^{rt}, \text{ and} \\ &\frac{\partial Q}{\partial w} \Big/ \frac{\partial Q}{\partial Z} = \frac{c(w,x) + b\phi e^{rt}}{PZ}. \end{aligned} \tag{2.14}$$

As the parameter b becomes very small, Equation 2.14 is the situation where water is treated as a free good, and the irrigator uses the quantity W' in Figure 2.4. More water is used than is socially optimal. The common property aspect of groundwater causes the problem to revert to one in which the solution is the same as static solution of section 2.2.2.

For the individual irrigator, it seems likely that the second polar case is the better approximation of reality. Farmers are well aware that the water table is falling throughout the area even under land that is not irrigated. They also know they have no legal claim on the water under their land when it seeps over their property line. Public awareness of the problem has stimulated the formation of non-market methods to control withdrawals. The non-market methods involve the formation of designated conservation districts[1] for groups of counties where a number of irrigators are concentrated and the water table is falling rapidly. There are probably not sufficient incentives to make these localized approaches work. The benefits of conservation by the members of the conservation district are shared with non-members outside the district. The district boundaries must terminate at state lines, diminishing the attractiveness of such associations. So far, only one of the several districts formed has established regulations to actually restrain withdrawals. This is in the Upper Republican Natural Resource District of Nebraska. It is not clear, moreover, whether such rules would hold up if challenged in court in Nebraska. It seems that they almost certainly would not in Texas, at least.

Consequently, it is assumed in the rest of the dissertation that the second polar case best describes the behavioral decisions made by irrigators. Irrigators know that depletions in groundwater will raise their costs, but their individual actions have little effect on the water table. Restraints by conservation districts will continue to be minimal. An overdraft of the aquifer results -- an overdraft in the sense that irrigators are using more water than is optimal, ignoring future benefits of conservation because of the problem of commonality.

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[1]More detail on groundwater conservation districts is given in Appendix B.

3. MODEL DESCRIPTION

The model used in this study is adapted from three previous models developed at the Center for Agricultural and Rural Development: the National Water Assessment Model (Meister and Nicol, 1975), the OBERS Model developed for the USDA largely by Boggess[1], and the CARD Energy Model (Dvoskin, Heady, and English, 1978). The "Ogallala Model," like its predecessors, can be divided into endogenous and exogenous components. The endogenous component consists of a recursive linear programming model which minimizes the costs of production and distribution of 11 endogenous crops subject to maximum constraints on land and water used and minimum constraints on product availability with predetermined relationships between yields, resource use, and costs of production, all by region. The linear programming model selects the regional levels of production, resource use, and crop and land prices. The exogenous component consists of a number of projections of resource use by the exogenous agricultural sector and changes in such variables as population, exports, income and yields which are used in estimating coefficients, and restraints for the endogenous linear programming model.

3.1. Regional Definition

The model is defined over the 48 contiguous states; interactions with the rest of the world are limited to an exogenously determined

[1]William Boggess, Assistant Professor, University of Florida. Much of the material in this model has not been documented but made available through personal communications.

level of exports. The contiguous states are partitioned into the 105 producing areas (PA's) shown in Figure 3.1. Distinct production activities and restraints are specified for each PA. The PA's are identical, with certain exceptions, to the Water Resource Council's "aggregate subareas" shown in Figure 3.2. Six of the aggregate subareas have been divided to make the following pairs of PA's: 55 and 56, 58 and 59, 65 and 66, 67 and 68, 72 and 73, and 74 and 75. The six aggregate subareas are divided because of significant differences in costs, yields, and production practices within these aggregate subareas.

The PA's can also be grouped into three zones with increasing disaggregation in the representation of production possibilities and constraints in each zone. The three zones are also shown in Figure 3.1. The most detailed representation is made for the Ogallala Zone, where restraints and production activities are specified for five land classes and irrigation from the Ogallala Aquifer is represented for eight distinct water situations. A single land class is used for PA's in the Eastern and Western zones, but three irrigation possibilities are specified in the Western Zone: irrigation with surface water, irrigation with groundwater, and production without irrigation. No disaggregation is made for irrigation in the Eastern Zone. Irrigation with surface water and irrigation with groundwater from aquifers other than the Ogallala are also represented in the Ogallala Zone. The PA's in the Western and Ogallala zones account for nearly 95 percent of all irrigation water used in the contiguous states.

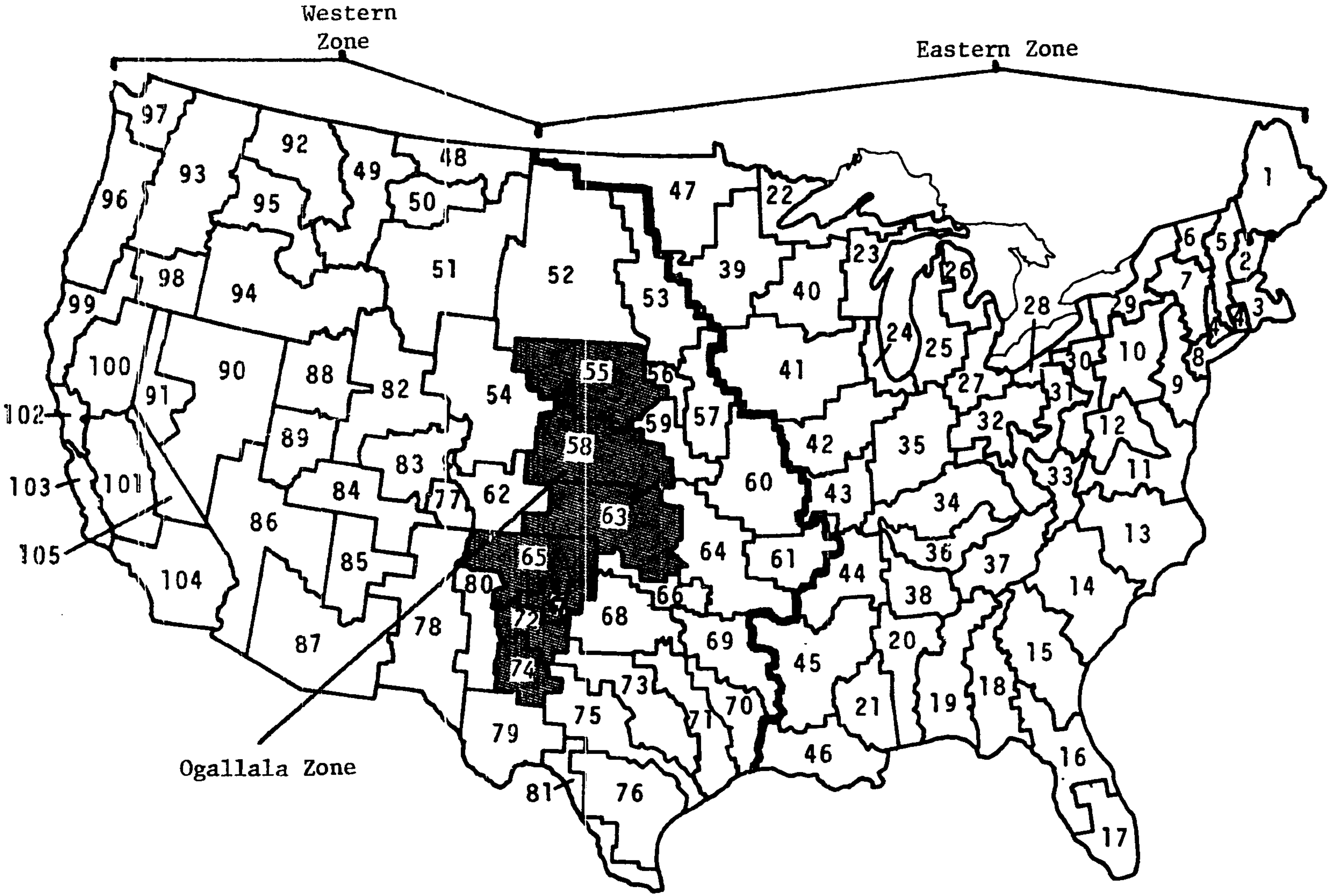

Figure 3.1. The 105 producing areas and the three zones

Figure 3.2. The aggregate subareas

Results are also reported on the basis of the zones. The Ogallala Zone is disaggregated for reporting results into the North, Central, and South Ogallala, which consist of PA's 55 and 58, 63 and 65, and 67, 72, and 74, respectively. This is because irrigation in the Ogallala Zone has developed unevenly and may have different future courses of development as pointed out in Chapter 1.

The PA's are aggregated into the 28 market regions (MR's) as shown in Figure 3.3. Each MR is identified by a major city within its area. Transportation of commodities is defined between these cities in the linear programming model. Most commodity constraints are set at the MR level. The exception is cotton, which is constrained at the national level. Nitrogen available from livestock wastes, nitrogen, and energy prices all function at the MR level of aggregation. The model determines crop prices at the market region level, but these are weighted into the zones for reporting results.

3.2. Activities

The primary variables or activities of the linear programming model are rotations each of which represent a combination one to four of the 11 endogenous crops: barley, corn grain and silage, cotton, legume and non-legume hay, oats, sorghum grain and silage, soybeans, and wheat. Coefficients are developed for each rotation in each PA reflecting amounts of water, nitrogen, energy, yields, and costs of all inputs except land. The cost of land and returns to management are determined endogenously in the model. Rotations are scaled to one acre of land so all other coefficients are in units per acre.

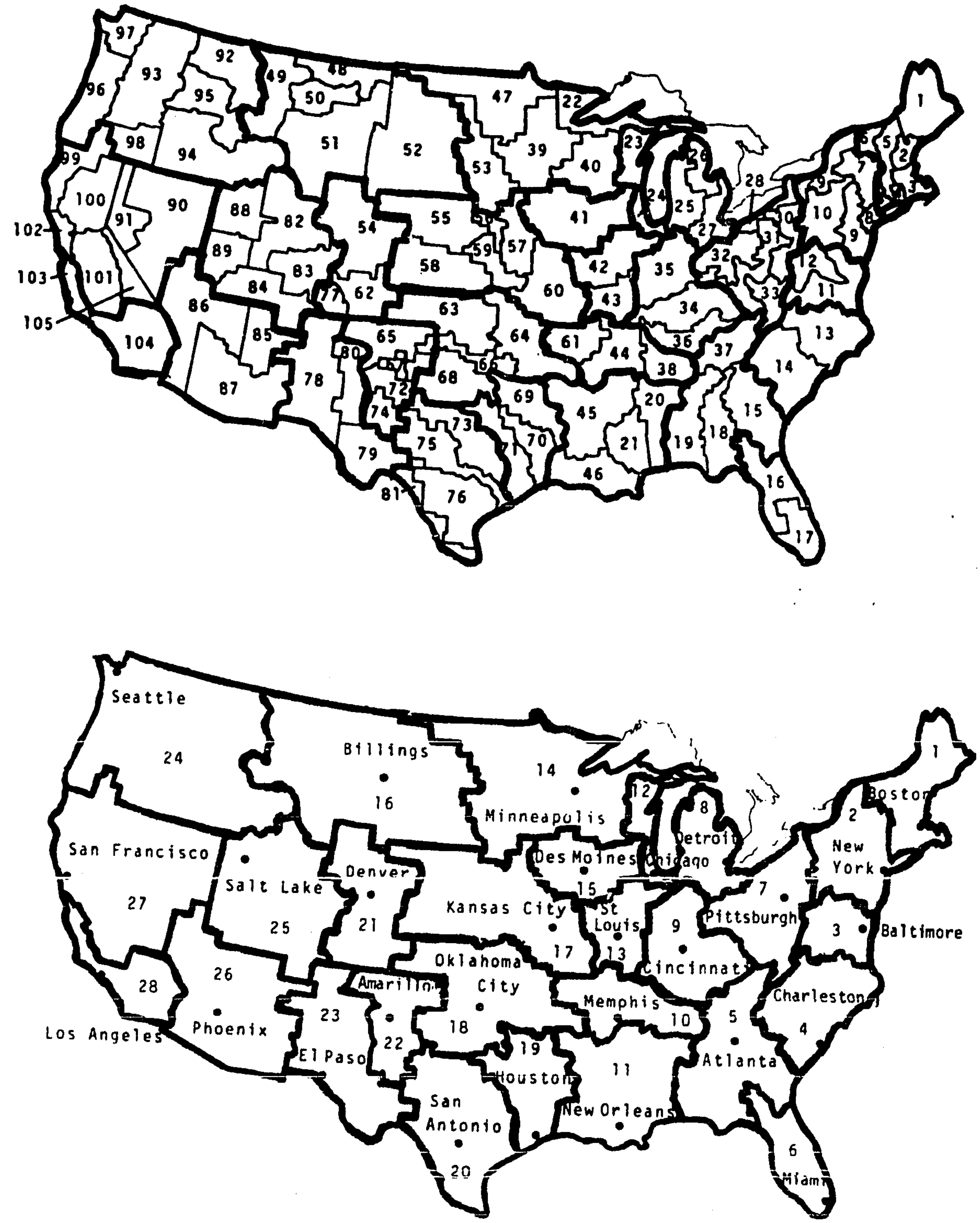

Figure 3.3. The 28 market regions

Other variables represent interregional transfers of crops and water which allow the model to simulate interregional competition.

3.2.1. Rotations

Rotations represent production of the endogenous crops in fixed proportions. A number of basic rotations typical of local production practices are specified for each PA. Coefficients for each rotation are a weighted average of the coefficients for each crop in the rotation. The coefficients estimated for each rotation are costs (which include energy costs, pesticides, labor, machinery, ownership costs for capital goods, and costs of other miscellaneous inputs), yields, and the quantity of nitrogen fertilizer, other fertilizers, and water (where applicable) associated with each yield. Yield and fertilizer coefficients for rotations which contain legume hay or summer fallow are modified appropriately.

A number of activities are included in the model for different variations of each basic rotation. Three types of tillage practices and two fertilizer levels are variations included for all rotations. The three tillage practices are fall moldboard plowing, spring chisel plowing, and minimum tillage. Different costs for machinery and pesticides, different energy coefficients, and different yields are estimated for each practice. In addition, two levels of water use are included for all irrigated rotations. The basic relationship between yields, fertilizer, and water was estimated by Stoecker (1974). Combinations of alternate levels of nitrogen and water and resultant yields are estimated following the data and procedure in English and

Dvoskin (1977). All variations of each rotation are duplicated on each land class and, where appropriate, for each irrigation possibility. Consequently, the number of variations in the model for each non-irrigated rotation is six, 24 for irrigated rotations in the Western Zone, and up to 408 for irrigated rotations in the Ogallala Zone. Costs of production, by land class and by tillage practice, were estimated by Boggess for the OBERS model. Energy coefficients by tillage practice were taken from Dvoskin, Heady, and English (1978). Energy coefficients for irrigation are given in Appendix C. Water coefficients were taken from the Department of Agriculture (1976).

In addition, a number of activities are included which produce only hay and use only water. These activities are bounded by the amount of irrigated hayland available in a region. They allow the model to compete for water which may be used on hayland which is not included endogenously in the model.

3.2.2. Water and commodity transfers, land conversion

Commodity transfers are defined for all crops (except hay, silage, and cotton) between all contiguous MR's and between selected non-contiguous MR's. More information on costs and routes are given in Meister and Nicol (1975). The energy coefficients were taken from Dvoskin, Heady, and English (1978) and assume one gallon of diesel per 235 ton miles reflecting railroad fuel efficiencies and distances between principal cities in Figure 3.3.

Water transfers are described in more detail in Short and Turhollow (forthcoming). Two sets of water transfers are defined in the model; the first represents the natural flow of surface water along the river courses between producing areas. The pattern of these transfers is shown in Figure 3.4. The second set (Figure 3.5) represents artificial transfers along canals and, in a few cases, corrections for the establishment of PA boundaries along county lines rather than natural watersheds. Costs are established for these transfers representing canal operation costs, but no charges are used on the natural transfers.

In addition, activities are included to allow the conversion of pasture and forestland to non-irrigable cropland. The prices for conversion used are given in Meister and Nicol (1975). These activities are also bounded at the levels given by Meister and Nicol. A total of 11 million acres may be converted by 1990 and 18 million by 2000.

3.2.3. The objective function

The objective function minimizes the sum of the rotation costs, and water and commodity transfer costs. The expression to be minimized can be expressed mathematically as:

$$\sum_{rtnpl} (CD_{rtnpl} NR_{rtnpl} + \sum_{ws} CR_{rtnplws} IR_{rtnplws}) \tag{3.1}$$

$$\sum CC_p LC_p + \sum_{uv} CW_{uv} W_{uv} + \sum CT_{cij} T_{cij},$$

r = 1,2, ... for the rotation,

t = 1,2,3 for the tillage practice,

n = 1,2 for the nitrogen level,

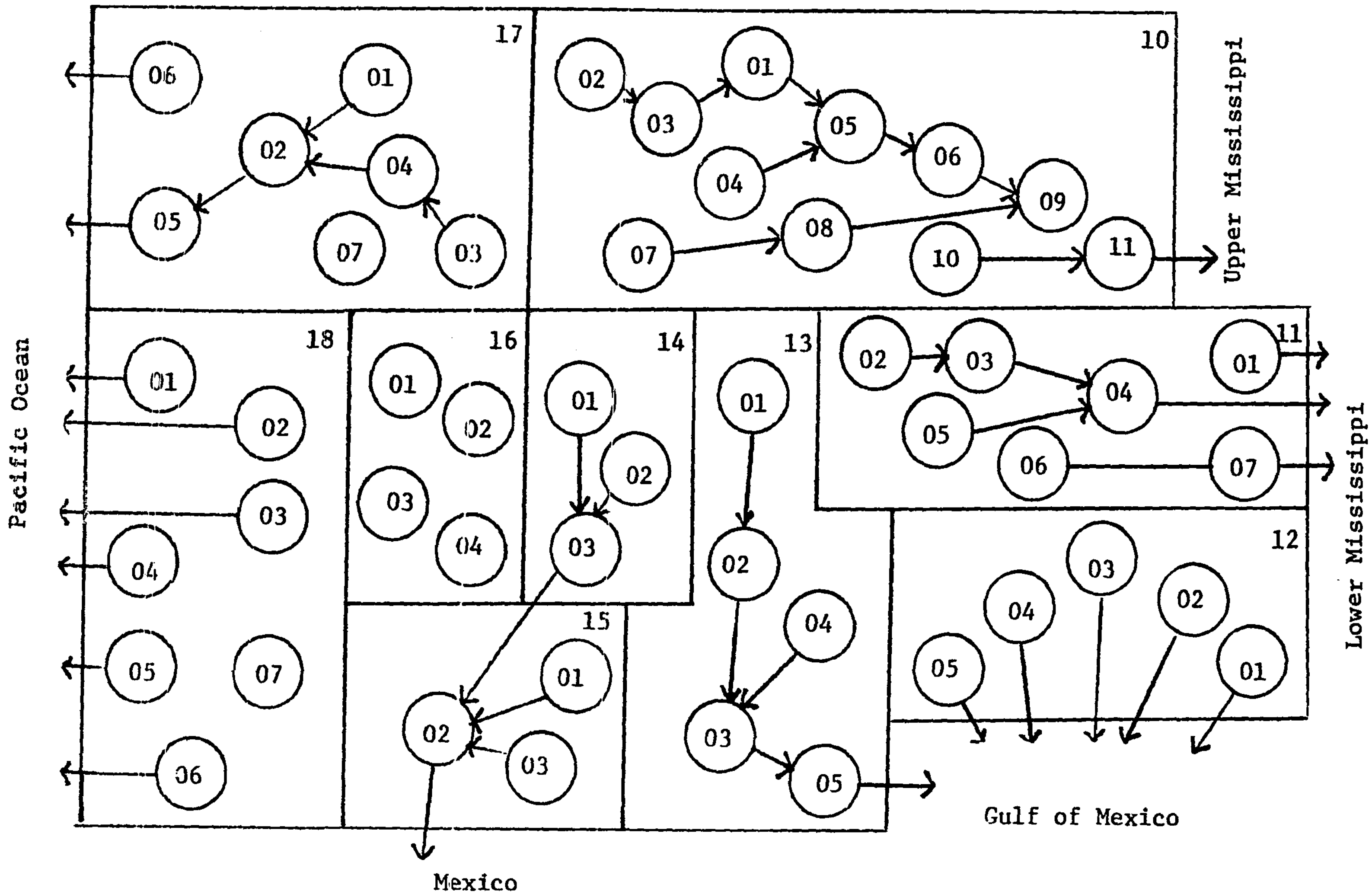

Figure 3.4. Natural transfers between aggregate subareas

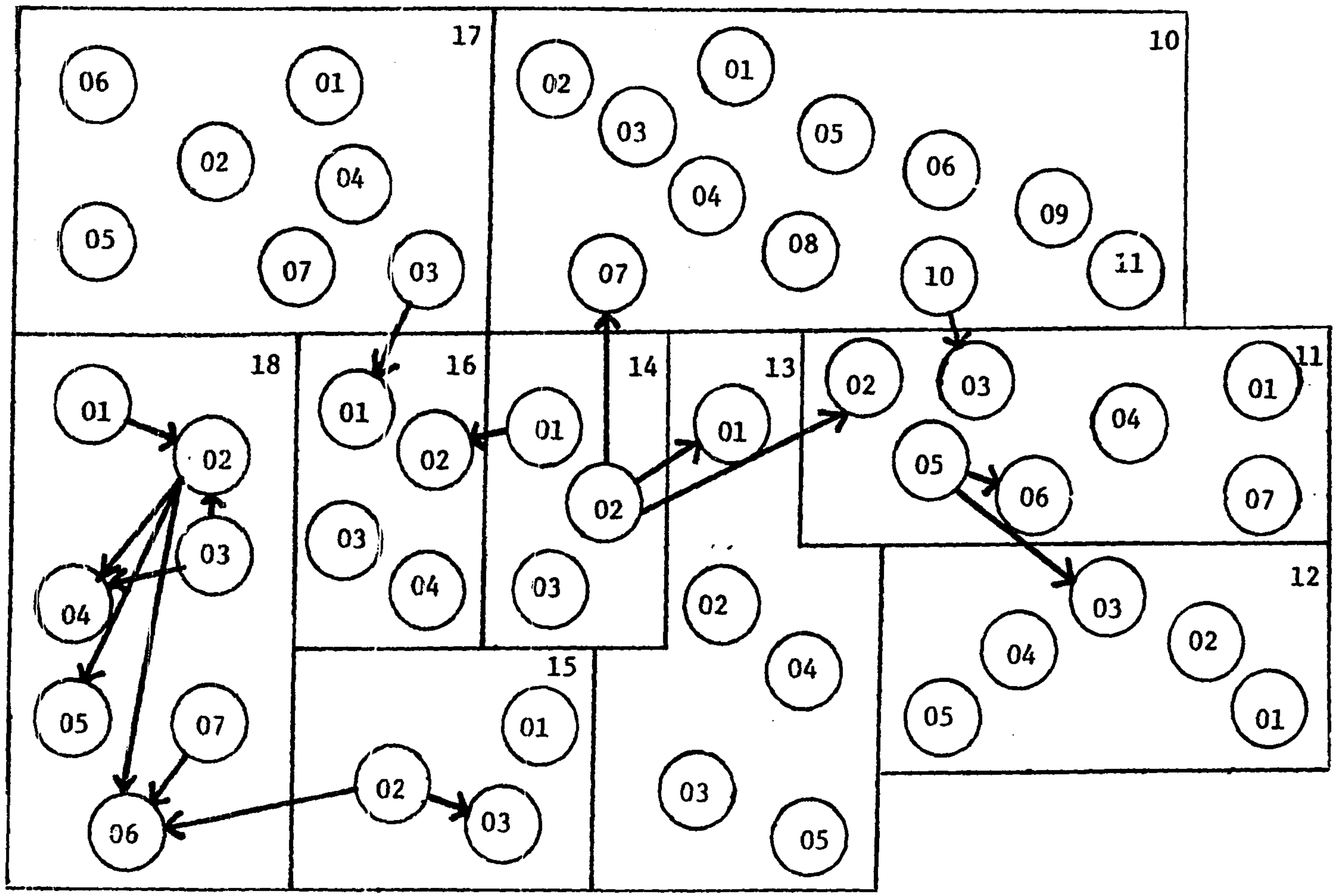

Figure 3.5. Artificial transfers allowed between aggregate subareas

$p = 1,2, \ldots, 105$ for the PA,

$l = 1,2, \ldots, 5$ in Ogallala Zone and D elsewhere for the land class,

$w = 1,2$ for the water level,

$s = 1,2, \ldots, 8$ for the water situation for the Ogallala Aquifer or 1,2 for surface and groundwater otherwise,

$u,v = 1,2, \ldots, 51$ for the ASA,

$c = 1,2, \ldots, 7$ for transferable crops,

$i,j = 1, 2, \ldots, 28$ for the MR,

where

CR is rotation cost per acre,

NR is area for the non-irrigated rotation selected,

IR is the area of the irrigated rotation selected,

CC is the cost of forest or pasture land conversion per acre,

LC is the amount area of forest or pasture converted,

CW is the cost of artificial water transfer per acre foot,

W is the amount of water transferred,

CT is cost of commodity transfer per unit, and

T is amount of commodity transfer.

3.3. Constraints

Constraints are defined in the linear programming model at all three levels of aggregation: national, market region, and producing area. The type of constraints established varies, however, by zone. The model is driven by minimum constraints on product availability or demands. Demands must be met at the market region or, in the case of cotton, national level, and are independent of the zones. The demands can be met by commodities produced in the area where it is needed or produced elsewhere and transferred.

The main limitations on production are land and water constraints at the producing area level. Land and water demands for exogenous crops, livestock, and non-agricultural uses are determined exogenously and constraints established so that these resource demands are all satisfied. Other resources such as energy and nitrogen influence production by their cost but do not limit production, because unbounded variables representing purchases of these resources are included in the model.

The method of estimating land and water restraints does vary from zone to zone. This is because of the different structure of agriculture in the contiguous states and because of our particular interest in the Ogallala Zone. Land in the Ogallala Zone is divided into five land classes, but only a single land class restraint is used in other zones. The constraints for non-irrigable land may be written, therefore, as:

$$\sum_{rtn} NR_{rtnp} - LT_{ps} + LC_p \leq L_p \qquad (3.2a)$$

for the Eastern and Western zones and, for the Ogallala Zone, as:

$$\sum_{rtn} NR_{rtnp1} - LT_{ps1} - LOT_{ps1} + LC \leq L_{p1} \qquad (3.2b)$$

$r = 1,2, \ldots$ for the rotation,

$t = 1,2,3$ for the tillage practice,

$n = 1,2$ for the nitrogen level,

p = 55, 58, 63, 65, 67, 72, 74 for the PA's in the Ogallala Zone, or

p = 1, 2, ..., 105 for the PA's (excluding the seven Ogallala PA's) otherwise,

l = 1, 2, ..., 5 for the land classes in the Ogallala Zone,

s = 1, 2 for the source of water, or

s = 1, 2, ..., 8 for the water situations in the Ogallala Aquifer,

where

NR is the amount of non-irrigable land selected,

LT is the amount of land that could be irrigated but the model elects to use without irrigating[1],

LC is the amount of forest and pasture land converted to cropland, and

L is the maximum amount of non-irrigable cropland available as shown in Table 3.1.

Table 3.1 is based upon data from Boggess. The amount of irrigable land and the amount of surface water available are also constrained in the western zones. Land irrigated from the Ogallala Aquifer is constrained by water situation as well as land class. The rationale for these constraints and the methods used in estimating them is explained in the next two subsections. The model allows all such land to be used without irrigation as well.

3.3.1. Land and water constraints for irrigation in both the Ogallala and Western zones

Irrigated activities in the Western and Ogallala zones are divided into two categories depending upon whether surface water or groundwater

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[1]Land transfers are discussed in section 3.3.2.

Table 3.1. Constraints for non-irrigable land by producing area for 1990 and 2000

PA	LC	1990	2000
		- 1,000 acres -	
1	NA	510.510	515.600
2	NA	61.920	62.100
3	NA	33.960	37.400
4	NA	63.810	65.500
5	NA	230.570	234.600
6	NA	295.110	295.300
7	NA	844.910	847.600
8	NA	63.400	65.500
9	NA	1,611.240	1,620.700
10	NA	2,748.180	2,751.900
11	NA	2,562.320	2,579.400
12	NA	1,290.080	1,294.500
13	NA	4,077.310	4,125.300
14	NA	4,626.950	4,647.200
15	NA	3,031.980	3,036.700
16	NA	1,230.040	1,197.600
17	NA	228.900	211.700
18	NA	2,430.680	2,426.700
19	NA	2,149.400	2,145.900
20	NA	1,726.820	1,729.800
21	NA	1,401.850	14,004.800
22	NA	439.980	439.900
23	NA	2,808.450	2,811.400
24	NA	2,171.400	2,173.600
25	NA	4,878.400	4,889.200
26	NA	2,340.550	2,343.600
27	NA	6,409.900	6,122.000
28	NA	996.740	1,003.500
29	NA	2,184.030	2,195.600
30	NA	753.850	754.600
31	NA	2,368.950	2,372.000
32	NA	5,895.270	5,898.500
33	NA	296.990	297.600
34	NA	5,123.02	5,137.600
35	NA	13,411.800	13,417.700
36	NA	2,042.780	2,047.400
37	NA	1,104.170	1,106.700
38	NA	2,578.400	2,580.200
39	NA	12,401.740	12,391.400
40	NA	6,249.420	6,250.500
41	NA	24,766.520	24,772.700
42	NA	13,014.240	13,017.800
43	NA	4,721.240	4,721.900

Table 3.1. Continued

PA	LC	1990	2000
		- 1,000 acres -	
44	NA	9,122.670	9,064.700
45	NA	7,613.120	7,603.300
46	NA	2,320.430	2,267.200
47	NA	18,557.940	18,672.600
48	NA	4,514.720	4,514.190
49	NA	4,009.240	4,010.500
50	NA	898.840	899.110
51	NA	2,054.761	2,042.920
52	NA	13,124.117	13,174.010
53	NA	13,872.363	13,917.750
54	NA	4,652.458	4,669.180
55	1	117.925	14.51
	2	209.073	42.24
	3	179.520	86.61
	4	588.408	588.71
	5	269.919	274.000
56	NA	2,735.324	2,718.890
57	NA	9,960.770	9,954.840
58	1	850.851	826.090
	2	3,569.926	3,373.160
	3	1,733.548	1,676.590
	4	2,058.850	2,058.850
	5	803.100	803.100
59	NA	4,068.511	3,926.450
60	NA	9,656.579	9,656.800
61	NA	1,348.810	1,309.520
62	NA	1,889.179	1,883.390
63	1	2,094.580	2,073.100
	2	6,184.849	6,112.040
	3	2,945.795	2,932.180
	4	2,244.696	2,244.690
	5	544.820	544.820
64	NA	4,769.255	4,762.710
65	1	0.000	0.000
	2	893.992	940.680
	3	231.752	273.880
	4	509.610	509.970
	5	171.224	171.170
66	NA	1,832.148	1,879.920
67	1	10.701	10.230
	2	588.479	588.480
	3	105.388	119.710
	4	124,272	124.310
	5	29.723	29.730
68	NA	6,099.148	6,173.530

Table 3.1. Continued

PA	LC	1990	2000
		- 1,000 acres -	
69	NA	1,340.283	1,377.770
70	NA	393.341	392.720
71	NA	2,306.750	2,316.650
72	1	185.154	221.550
	2	986.291	1,122.480
	3	472.169	510.000
	4	237.290	237.290
	5	0.000	187.05
73	NA	5,172.177	5,183.270
74	1	0.000	0.000
	2	209.465	221.560
	3	469.186	526.200
	4	663.960	664.750
	5	247.600	247.720
75	NA	3,096.348	3,101.440
76	NA	3,343.074	3,363.870
77	NA	0.000	0.000
78	NA	128.584	118.760
79	NA	7.361	7.360
80	NA	0.000	4.220
81	NA	354.637	358.330
82	NA	24.375	14.160
83	NA	21.308	13.090
84	NA	174.643	171.180
85	NA	27.199	26.440
86	NA	0.000	0.000
87	NA	38.689	148.74
88	NA	544.476	518.910
89	NA	85.590	85.590
90	NA	0.000	0.000
91	NA	0.000	0.000
92	NA	572.190	568.950
93	NA	5,644.800	5,580.370
94	NA	1,231.030	763.780
95	NA	2,183.620	2,155.900
96	NA	1,358.460	1,346.140
97	NA	261.690	273.670
98	NA	108.120	100.590
99	NA	142.460	132.150
100	NA	825.280	795.160
101	NA	420.910	0.000
102	NA	182.830	176.450
103	NA	666.980	660.450
104	NA	198.000	177.610
105	NA	0.000	0.000

is used. The dichotomy is important, because costs and energy needs are different in the same PA according to the source of water. Irrigation with groundwater and with surface water also differ in how they interact with other uses in limiting irrigation. Another important difference for modeling is that surface water is purely a flow resource, whereas groundwater has aspects of both a stock and a flow resource.

Both sources of water are closely tied in use to the land with which they are found. Surface water more readily admits to competition between uses and between users in different regions because of interregional and intraregional transfers. Because surface water is a flow resource, all uses must be limited by the amount that becomes available from precipitation in a given year. Consequently, constraints are necessary to represent the competition for surface water. In developing the constraints, it is assumed that non-agricultural users, livestock demands, and the irrigation of exogenous cropland are higher valued uses than the irrigation of endogenous cropland. The constraints for surface water availability are calculated as the difference between total water available and the water required by these exogenous demands. The net effect of transfers between aggregate subareas and water used in crop production in the linear programming model must be less than this difference:

$$\sum w_{rp} R_{rp} + \sum NT_{pg} + \sum AT_{pq} \leq WA_p - NAG_p - EAG_p \qquad (3.3)$$

$r = 1, 2, \ldots$ for the irrigated rotations,

$pq = 1, 2, \ldots, 52$ for the aggregate subareas, where

- w is the water use per acre,
- R is the number of acres,
- NT is the transfer of water between ASA's along a natural water course,
- AT is the transfer of water between ASA's along a canal,
- NAG is the sum of the non-agricultural demands for water, and
- EAG is the sum of the exogenous agricultural demands for water.

More detail on how the surface water constraints are estimated is given in Short and Turhollow (forthcoming).

Irrigation with surface water is also limited by the amount of land that can be irrigated. Not all of the land within a PA can be irrigated with surface water even if there is a surplus. Consequently, a constraint is needed to represent the amount of land that can be irrigated with surface water. But data are not directly available on the amount of land irrigable with surface water, so it is necessary to estimate these data from diverse sources.

Surface water for irrigation may originate from either individual on-farm sources or from irrigation organizations. There is little scope for expansion in the area irrigated from on-farm sources of surface water in the Western and Ogallala zones. The area irrigated from on-farm sources is given in the 1959 Census of Agriculture (Department of Commerce, 1962) by county and by state. The amount of water derived from this source is given in the 1969 Census by state (Department of Commerce, 1973). If the water from on-farm sources of surface water by state in 1969 divided by the average amount of water applied per acre by state is used as an estimate of the areas irrigated from on-farm sources of surface water, the resultant estimates are very close to the areas reported directly in the 1959 census. Therefore, it is assumed that the area that can be irrigated from on-farm sources of surface water will be the same in 1990 and 2000 as the areas irrigated by state in 1969 estimated as just described. The 1969 areas irrigated by state are weighted to producing areas using weights derived from county level data reported in the 1959 census. The areas estimated in this manner are reported in Table 3.2.

The area irrigated with surface water from irrigation organizations in 1969 is also reported in Table 3.2. These data were taken from the 1969 Census where areas are given by Water Resource Council Subareas. For a few PA's, it is necessary to make assumptions to break apart data presented in aggregate form to protect confidentiality. The areas irrigated with water from irrigation organizations are adjusted for groundwater used by organizations and for transfers between organizations assumed to be 100 percent surface water. Water from irrigation organizations is approximately 97 percent surface water. New public developments expected to be "on-line" in 1990 and 2000, as reported in Meister and Nicol (1975), are also included in the area irrigable with water from irrigation organizations. The areas irrigated with water from on-farm sources and from irrigation organizations may be added to give total area irrigated with surface water including cropland for endogenous and exogenous crops and for irrigated hay and pasture land.

Table 3.2. Disaggregation of irrigated land by source of irrigation water

PA	Area irrigable from surface sources		Total area irrigable		Proportion irrigable with surface water	
	On-farm	Organization	1990	2000	1990	2000
	- 1,000 acres -					
48	34.084	123.551	280.073	280.064	.56	.56
49	434.554	580.078	1,105.986	1,105.164	.92	.92
50	53.390	57.721	147.189	147.195	.75	.76
51	245.893	1,128.218	1,428.139	1,423.598	.96	.97
52	74.379	108.946	307.274	307.625	.60	.58
53	8.813	71.784	138.228	138.230	.58	.58
54	541.493	1,733.843	2,419.249	2,419.723	.94	.94
55	52.901	585.182	2,181.331	2,181.849	.29	.29
56	5.124	0.000	159.973	160.019	.03	.03
57	1.462	0.000	36.309	36.326	.04	.04
58	26.489	134.108	1,195.227	1,195.762	.13	.13
59	28.066	0.000	1,038.089	1,038.237	.03	.03
60	0.798	0.000	5.494	5.493	.15	.15
61	0.000	0.000	20.289	59.843	.00	.00
62	75.387	431.001	635.718	635.801	.80	.80
63	15.894	51.083	1,847.237	1,849.752	.04	.04
64	7.513	0.000	40.732	40.729	.18	.18
65	25.042	75.083	1,412.231	1,412.253	.07	.07
66	1.794	0.000	46.797	46.828	.04	.04
67	6.734	0.000	672.219	672.215	.01	.01
68	33.804	59.256	539.503	539.793	.17	.17
69	13.869	0.268	37.778	37.796	.37	.37
70	29.765	97.350	183.876	183.873	.69	.69
71	56.643	98.268	521.304	521.304	.30	.30
72	28.198	0.525	3,006.710	3,006.867	.01	.01
73	34.621	34.031	237.267	237.282	.29	.29
74	2.049	0.000	733.808	733.827	.00	.00
75	47.289	66.018	426.159	426.127	.27	.27
76	45.802	50.183	488.278	488.218	.20	.20
77	74.677	521.083			1.00	1.00
78	19.759	352.124	505.026	505.202	.74	.74
79	7.257	13.420	288.522	288.503	.07	.07
80	13.185	61.751	211.832	211.923	.35	.35
81	116.416	620.270	814.313	814.311	.90	.91
82	259.232	600.758	1,038.035	1,037.939	.83	.83
83	232.504	583.019			1.00	1.00
84	30.658	306.728	386.693	386.550	.87	.87
85	4.022	19.283	33.700	33.722	.69	.69
86	11.227	330.325	375.741	377.236	.91	.91
87	22.366	276.853	972.924	978.822	.31	.31

Table 3.2. Continued

PA	Area irrigable from surface sources: On-farm	Area irrigable from surface sources: Organization	Total area irrigable: 1990	Total area irrigable: 2000	Proportion irrigable with surface water: 1990	Proportion irrigable with surface water: 2000
		- 1,000 acres -				
88	70.144	881.667			1.00	1.00
89	19.900	359.060	493.170	492.991	.77	.77
90	206.684	45.946	1,128.659	1,128.652	.22	.22
91	92.434	201.778	317.345	317.368	.93	.93
92	183.286	290.821	655.698	655.814	.72	.72
93	200.971	1,319.161	1,883.028	1,885.392	.81	.81
94	309.137	2,708.136	3,825.352	3,825.531	.79	.79
95	126.430	141.331	362.819	362.763	.74	.74
96	143.761	115.955	411.419	411.567	.63	.63
97	29.212	18.964	63.221	64.613	.76	.75
98	135.916	45.904	294.660	294.659	.62	.62
99	120.328	293.610			1.00	1.00
100	321.936	754.441	1,820.161	1,824.349	.59	.59
101	219.515	3,148.750	4,680.206	4,693.253	.72	.72
102	77.314	33.728	291.589	292.427	.38	.38
103	11.269	26.043	361.715	363.135	.10	.10
104	19.315	743.039	1,142.275	1,145.333	.67	.67
105	25.103	1.635	60.788	61.788	.44	.43

Boggess[1] projects total land irrigable and irrigable endogenous cropland for 1990 and 2000. Boggess' projections combine land irrigable with surface water and groundwater. They are derived from the 1967 Conservation Needs Inventory and include all land irrigated in 1967 adjusted for irrigation developments 1967-74 and for future public developments of irrigated land expected to be "on-line" in 1990 and 2000. The proportions of irrigated land which are irrigable with surface water are found by dividing the surface irrigable by all irrigable land. These proportions can then be used to disaggregate Boggess' irrigable endogenous cropland into land irrigable with surface water and land irrigable with groundwater. This procedure assumes that the proportions derived in Table 3.2 for aggregated irrigated land are valid for endogenous cropland. Table 3.3 shows the constraints for endogenous land irrigated with surface water that are derived using this procedure.

We now turn to constraints on irrigation with groundwater. In practice, groundwater is even more closely tied in use to the land than is surface although the opposite is probably the case in terms of water rights. In general, groundwater underlying cropland does not have competing uses either spatially or in terms of the purpose to which the water is applied. Aquifers contain a stock of water, so there is not a meaningful limit on the amount that would be pumped in a given year. But the amount of land overlying viable aquifers

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[1] William G. Boggess, Department of Agricultural Economics, Florida State University.

Table 3.3. Constraints on land irrigable with surface and groundwater

PA	Irrigable with surface water 1990	Irrigable with surface water 2000	Irrigable with groundwater[a] 1990	Irrigable with groundwater[a] 2000
	- 1,000 acres -			
48	68.78	68.80	53.44	53.40
49	504.48	504.26	45.42	45.04
50	53.17	53.19	17.27	17.29
51	626.33	628.06	45.99	56.63
52	89.40	77.78	103.60	117.54
53	77.57	77.43	62.97	67.17
54	1,176.11	1,206.78	254.51	229.39
55	527.83	528.13	452.60	55.44
56	4.95	4.94	178.60	195.42
57	1.55	1.15	30.74	33.49
58	162.35	162.34	111.20	111.49
59	27.77	27.74	1,245.00	1,387.16
60	0.78	0.78	5.28	5.66
61	0.00	0.00	20.29	37.46
62	367.04	368.06	104.86	111.91
63	66.92	66.92	332.70	275.24
64	3.60	3.81	27.25	34.78
65	150.38	151.47	0.00	0.00
66	0.62	1.43	25.04	18.97
67	1.81	1.81	0.00	0.00
68	55.48	81.89	415.51	321.60
69	8.83	8.81	58.33	21.41
70	60.76	56.51	32.14	30.28
71	85.80	81.39	217.26	206.97
72	4.72	5.08	64.87	64.90
73	41.94	41.46	111.27	110.23
74	2.34	2.34	84.87	85.32
75	57.72	54.86	174.76	166.77
76	59.11	57.07	257.70	248.71
77	262.55	266.42	0.00	0.00
78	272.19	273.54	119.84	130.33
79	19.66	19.69	263.61	262.71
80	69.28	69.42	130.78	130.85
81	515.95	500.65	92.67	90.86
82	367.43	367.70	93.84	103.54
83	282.36	283.50	7.66	22.90
84	187.32	187.54	25.73	36.65

[a]Excludes land irrigable from the Ogallala Aquifer in land classes 1, 2, and 3.

Table 3.3. Continued

PA	Irrigable with surface water		Irrigable with groundwater	
	1990	2000	1990	2000
		- 1,000 acres -		
85	14.29	14.30	7.66	8.43
86	154.12	156.38	25.73	26.72
87	257.35	258.87	629.47	666.72
88	501.60	510.22	15.21	24.05
89	291.53	292.05	87.86	87.73
90	84.14	84.20	294.89	294.83
91	111.43	111.56	8.76	8.79
92	149.54	150.22	59.32	60.79
93	900.28	871.68	278.45	310.36
94	1,944.51	1,949.35	816.66	989.10
95	139.34	138.82	69.88	81.58
96	129.93	119.28	82.06	79.52
97	5.20	1.67	4.34	4.87
98	121.44	121.43	80.15	82.94
99	247.06	247.44	6.50	10.31
100	323.35	293.61	242.31	234.15
101	2,223.30	2,224.85	916.37	954.25
102	37.26	38.24	64.57	68.78
103	4.91	5.25	46.81	52.24
104	402.00	404.70	213.63	224.17
105	2.89	2.85	3.69	0.00

does limit the amount of irrigation feasible with groundwater in a particular PA. Therefore, constraints are used to limit the land that can be irrigated with groundwater, but the amount of water that may be pumped is not restrained.

The procedure used to estimate PA constraints on the area that can be irrigated with groundwater differs for the Western and Ogallala zones. The area irrigable with groundwater is estimated from two sources. The proportion of Boggess' irrigable endogenous cropland that is irrigable with groundwater is estimated with the proportions in Table 3.2. Possible future private development of irrigation with groundwater is incorporated by adding the estimates of possible future conversions of non-irrigable endogenous cropland given by Meister and Nicol (1975, pp. 47-48). The constraints for non-irrigable land in Table 3.1 are adjusted accordingly. The final constraints for land irrigable with groundwater are given in Table 3.3. The constraints on the areas that may be irrigated may be summarized as:

$$\sum_{rtnw} IR_{rtnpws} + LT_{ps} \leq L_{ps} \tag{3.4a}$$

for the Western Zone, and for the Ogallala Zone, as:

$$\sum_{rtnw} IR_{rtnpws1} + LT_{ps1} \leq L_{ps1} \tag{3.4b}$$

$r = 1, 2, \ldots$ for the rotation,

$t = 1, 2, 3$ for the tillage practice,

$n = 1, 2$ for the nitrogen level,

p = 55, 58, 63, 65, 67, 72, 74 for the PA's in the Ogallala Zone, or

p = 1, 2, ..., 105 for the PA's (excluding the seven Ogallala PA's) otherwise,

w = 1, 2 for the water level,

s = 1, 2 for the source of water (groundwater or surface water),

l = 1, 2, ..., 5 for the land classes in the Ogallala Zone,

where

IR is the amount of irrigated land,

LT is the amount of irrigable land the model elects to use without irrigating, and

L is the maximum amount of irrigable endogenous cropland available as shown in Table 3.3.

This method of constraining irrigation implies that land cannot be irrigated with both surface or groundwater. According to the 1959 Census, only 3 percent of irrigated land in the 17 western states could be irrigated with either groundwater or on-farm sources of surface water. An additional 17 percent could be irrigated with water from irrigation organizations and some other source. The assumption held, therefore, for about 80 percent of the area irrigated in 1959. More recent data are not available, so no attempt was made to allow land to switch from irrigation with groundwater to irrigation with surface water or vice versa even though this is a possibility in some areas.

3.3.2. Constraints on irrigation from the Ogallala Aquifer

The basic problem in modeling the production possibilities and constraints of irrigation from the Ogallala Aquifer is to incorporate the variability. Because of variation in the depths to water and saturated thickness, some irrigation will remain profitable when irrigation elsewhere is not. The method adopted is to break the area using water from the Ogallala into water situations, as did Bekure and Coomer and Young, as described in Chapter 2.

Eight water situations are defined as the intersection of two saturated thickness intervals, 0-100 and 100+ feet, and four depth to water intervals, 0-50, 50-100, 100-200, and 200+ feet. The emphasis is on depth to water intervals, because energy costs are directly dependent on depth to water and pumping lift. Weights representing the proportions of land of each PA in each water situation for a given year are estimated as described in Appendix A. The proportions represent both currently irrigated and non-irrigated land in the eight water situations.

The weights are multiplied by the amount of endogenous cropland in the Ogallala counties by PA and land class to eliminate the constraints on irrigation from the Ogallala Aquifer, as shown in Table 3.4. The constraints can be expressed mathematically as in Equation 3.4b, where the subscript s would represent the eight water situations and the term L refers to the values in Table 3.4. The difference between one and the sum of the weights represents the proportion of non-irrigable land in the counties overlying the Ogallala counties. This, when added to the non-irrigable land in the rest of the counties in the Ogallala Zone, results in the constraints shown in Table 3.1. Constraints for the area irrigated with surface water and with groundwater from other aquifers are given in Table 3.3.

Table 3.4. Constraints on area irrigated from the Ogallala Aquifer by water situation and land class

Producing area	Land class	Water situation	1990	2000
			- 1,000 acres -	
55	1	1	48.591	34.677
		2	48.591	34.677
		3	103.987	118.641
		4	23.113	41.908
		5	114.509	72.396
		6	114.509	72.396
		7	272.333	259.529
		8	114.603	147.671
	2	1	93.567	70.113
		2	93.567	70.113
		3	203.632	228.290
		4	61.039	101.600
		5	220.304	153.246
		6	220.304	153.246
		7	491.853	456.971
		8	204.288	250.723
	3	1	58.318	43.398
		2	58.318	43.398
		3	115.634	127.177
		4	38.779	59.992
		5	156.505	115.735
		6	156.505	115.735
		7	305.446	292.282
		8	124.385	154.474
58	1	1	25.684	21.836
		2	25.684	21.836
		3	105.534	96.230
		4	50.848	71.166
		5	9.272	6.329
		6	9.272	6.329
		7	84.019	66.112
		8	46.143	53.004
	2	1	266.789	223.920
		2	266.789	228.920
		3	948.913	889.453
		4	487.294	605.564
		5	129.238	99.621
		6	129.238	99.621

Table 3.4. Continued

Producing area	Land class	Water situation	1990	2000
			- 1,000 acres -	
		7	747.361	630.885
		8	492.315	548.186
	3	1	65.644	56.974
		2	65.644	56.974
		3	218.127	207.448
		4	110.378	148.255
		5	37.638	28.793
		6	37.638	28.793
		7	202.682	169.029
		8	187.215	203.509
63	1	1	30.831	27.522
		2	82.840	77.527
		3	114.298	104.589
		4	92.413	111.550
		5	30.088	25.263
		6	115.232	103.577
		7	245.462	226.193
		8	105.255	125.347
	2	1	83.724	75.729
		2	224.169	217.409
		3	222.145	214.296
		4	136.603	168.875
		5	83.338	71.709
		6	291.244	267.912
		7	575.266	539.277
		8	208.265	246.407
	3	1	19.276	17.318
		2	60.934	58.609
		3	60.837	57.743
		4	41.080	49.832
		5	19.641	17.037
		6	81.365	75.611
		7	172.054	163.017
		8	57.743	68.096
65	1	1	0.000	0.000
		2	0.000	0.000
		3	0.000	0.000
		4	0.000	0.000

Table 3.4. Continued

Producing area	Land class	Water situation	1990	2000
			- 1,000 acres -	
		5	0.000	0.000
		6	0.000	0.000
		7	0.000	0.000
		8	0.000	0.000
	2	1	32.185	30.820
		2	42.221	41.577
		3	77.841	78.181
		4	318.752	402.400
		5	51.886	44.730
		6	135.232	115.528
		7	340.965	288.026
		8	889.935	855.375
	3	1	55.414	54.246
		2	48.520	47.813
		3	85.873	83.184
		4	169.415	201.821
		5	53.086	49.395
		6	129.174	117.151
		7	260.490	236.250
		8	330.581	328.485
67	1	1	1.095	0.932
		2	2.216	1.905
		3	4.113	3.521
		4	4.360	5.157
		5	0.022	0.007
		6	0.066	0.031
		7	0.339	0.112
		8	0.755	0.440
	2	1	29.523	25.850
		2	93.685	78.219
		3	278.600	238.597
		4	394.362	446.705
		5	1.422	0.756
		6	6.362	3.675
		7	69.783	41.746
		8	140.112	120.665
	3	1	12.490	11.476
		2	32.257	27.962

Table 3.4. Continued

Producing area	Land class	Water situation	1990	2000
			- 1,000 acres -	
		3	87.728	76.661
		4	114.744	129.425
		5	0.896	0.495
		6	2.208	1.381
		7	23.688	15.016
		8	46.028	41.326
72	1	1	19.621	17.280
		2	37.103	34.814
		3	77.245	69.595
		4	129.138	168.430
		5	7.766	3.406
		6	18.139	10.810
		7	52.296	24.740
		8	120.977	91.005
	2	1	97.014	87.332
		2	176.121	162.342
		3	423.281	365.920
		4	586.663	769.928
		5	22.063	11.424
		6	49.351	31.593
		7	228.641	106.202
		8	472.142	368.809
	3	1	73.046	68.467
		2	102.753	99.504
		3	178.111	169.592
		4	119.731	195.095
		5	15.529	7.420
		6	34.888	21.687
		7	72.368	40.628
		8	106.962	90.248
74	1	1	0.000	0.000
		2	0.000	0.000
		3	0.000	0.000
		4	0.000	0.000
		5	0.000	0.000
		6	0.000	0.000
		7	0.000	0.000
		8	0.000	0.000

Table 3.4. Continued

Producing area	Land class	Water situation	1990	2000
			- 1,000 acres -	
	2	1	35.721	31.013
		2	56.051	53.078
		3	66.564	64.877
		4	15.825	20.390
		5	9.874	8.436
		6	17.898	15.920
		7	9.133	8.382
		8	1.020	1.358
	3	1	104.773	89.570
		2	178.353	161.611
		3	207.530	202.077
		4	51.568	67.682
		5	16.095	10.570
		6	32.414	24.625
		7	20.585	19.323
		8	3.944	5.187

3.3.3. Demands and minimum quantities produced

Domestic demands are estimated for domestic consumption, livestock feed requirements, other uses, and net exports. The total demand for all uses constitutes the minimum market region constraints on commodity availability. Consumption demands and the demands for other uses are taken from Meister and Nicol (1975). Livestock feed demands are estimated by Boggess[1]. Export demand is set at two different levels for 1990 and one level for 2000 and weighted to market region using a set of weights as described by Meister and Nicol. The level of exports used is given in Table 3.5.

Table 3.5. Alternate levels of exports assumed in the model

Crop	Units	1990		2000
		A	B	
Feed grains:				
Corn	10^6 bushels	3,214	4,821	5,424
Sorghum	"	786	1,179	1,326
Barley	"	46	69	78
Oats	"	18	27	30
Wheat	"	2,856	2,856	3,213
Soybeans	"	1,680	1,680	1,890
Cotton	1,000 bales	4,743	4,743	4,743

Both levels of exports assumed for 1990 are high but not unreasonable in terms of the trends in export growth over recent decades. The trends over the last few decades have been for a steady increase in

[1]William G. Boggess, Department of Agricultural Economics, Florida State University, personal communication.

yields and fertilizer use. These trends are incorporated in projections of yields for 1990 and 2000. Consequently, a growth in exports similar to the historical patterns is needed if the model is not to be dominated by excess capacity.

A level of exports was selected for 1990 so that the area irrigated in the Ogallala Zone would be roughly similar to what it has been in the last census. This level of exports represents a tripling of the exports of feed grains, wheat, and soybeans over the average level of exports in the period 1974-77. In light of recent export growth, the estimate is optimistic but not unwarranted. To show the effect of a lower rate of export growth, a lower level of exports is assumed for one alternate solution of the model for 1990. The alternate level of exports consists of a doubling of feed grain exports and a trippling of exports of soybeans and wheat.

Also given in Table 3.5 are demands for 2000. Only a single level of demands is used for 2000. The 2000 demands represent a moderate increase over the demands for 1990 and may therefore represent a more conservative estimate of demand.

3.4. Solutions

A total of five solutions to the model is obtained. The solutions are identified epithetically in Table 3.6. Solution I has a high level of exports and moderate level of energy prices. The high level of demands in 1990 is increased only slightly and labeled moderate demands in 2000. High energy prices in 1990 represent a quadrupling of base energy prices which are an average of energy

Table 3.6. Differences in assumptions for model solutions

Year	Solution	Demands	Energy prices
1990	I	High	Moderate
	II	High	High
	III	Moderate	Moderate
2000	I	Moderate	Low
	II	Moderate	Moderate

prices over the period 1975-79. Moderate energy prices in 1990 are a doubling of the base energy prices. Energy prices that are moderate in 1990 are relabeled as low for 2000, while high energy prices for 1990 are considered only a moderate level of energy prices in 2000. Three solutions are for 1990 and two for 2000.

The solutions for 1990 are designed to show the comparative effects of further rises in energy prices and a lower level of demands. Solutions II and III will be compared with Solution I to illustrate the impacts of these changes. The effect of the declining water table is estimated from analysis of the solutions comparing the area irrigated with the area that would be irrigated if the water table did not change over the period 1977-1990. The assumption is made that production lost through the declining water table is not enough to significantly affect national prices and land use patterns. The purpose is to estimate the effects of the changing water table on economic and resource variables in the Ogallala Zone where locally significant changes should result.

The two solutions estimated for 2000 both are linked with Solution I, 1990, as follows. The level of water withdrawals from the Ogallala

Aquifer selected in 1990 is compared with the level of withdrawals in 1974. The rates of decline in the North, Central, and South Ogallala zones are increased or decreased in proportion to the ratios of water withdrawn. Therefore, the weights used in estimating irrigation constraints in the Ogallala Zone assume a pattern of withdrawals in the period 1990-2000 similar to that selected by the model in Solution I.

Comparison of Solutions I and II for the year 2000 is used to compare the effect of increasing energy prices with the declining water table in the more distant future with further aquifer depletions.

4. RESULTS

A summary of the main features is given in this chapter. The material is developed from the linear program solution and data sets used in preparing the coefficients for the model. Solutions I and II for 1990 and 2000 are compared to show the effects of the rise in energy prices. Solutions I and III for 1990 are compared to show the effects of decrease in demand. The effect of the fall of water table varies for each solution.

4.1. Solution I 1990: The Base

Solution I 1990 is discussed in this section, because it is the base solution to which others are compared. This solution assumes a high level of exports, 1990 technology,[1] moderate energy prices, as well as an equilibrium optimal distribution of production,[2] all of which make the solution not directly comparable to the current situation.

4.1.1. Prices and resource use in Solution I

A result, primarily of the level of exports and energy prices, is that crop prices are high. Corn, cotton, soybean, and wheat prices

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[1]Basically, trend increases in yields, livestock feed conversion, fertilizer use, and diminished supplies of land and water due to changes in exogenous agricultural and non-agricultural sectors.

[2]Optimal in the sense that farmers are assumed to only minimize costs or maximize net returns. Risks and attitudes to risks are ignored, and capital like all resources except land and water is perfectly mobile, but demands are fixed regionally.

are \$2.95/bu., \$2.59/bale, \$7.03/bu., and \$5.54/bu., respectively. The changes assumed in yields would tend to reduce prices, but these effects are not as strong as that of high demand and energy prices.

The high level of demands also leads to a fairly high level of resource use, especially resources which are substitutes for energy. Land use is shown in Table 4.1. Nearly all of the land available is

Table 4.1. Land use in Solution I 1990

Item	Most productive use[a]	Other use	Total
	- 1,000 acres -		
Cropland irrigable with surface water	9,710	4,600	14,310
Cropland irrigable with groundwater	4,839	2,760	7,599
Cropland irrigable from Ogallala Aquifer	7,304	12,466	19,770
Private irrigation development	843	733	1,576
Convertible pasture land	4,597	0	4,597
Convertible forest land	6,445	153	6,595
Non-irrigable cropland	329,126	3,119	332,245

[a]The most productive use is as irrigated cropland for the first four items and as non-irrigated cropland for the last three items.

brought into production in its most productive use. All but 0.9 percent of the non-irrigable cropland is used in the production of the endogenous crops. All of the convertible pasture land is used for the production of the endogenous crops and 98 percent of the forest land as well. A lot of the irrigable land is not irrigated: 32, 36, 47, and 64 percent, respectively, of land irrigable with surface water, groundwater, new private developments of groundwater, and from the Ogallala Aquifer.

There were 34.1 million acres irrigated in the Western and Ogallala zones of the model in 1969, but 5.2 million acres were in exogenous crops (Department of Commerce, 1973). In addition to the 22.7 million acres of endogenous cropland irrigated, as much as seven million acres of exogenous hay and pasture are also irrigated. The amount of land irrigated in the Ogallala Zone also accords well with historical practices, especially when an allowance is made for the area not irrigated because of the decline of the water table.

Several factors are involved in explaining why even more land is not irrigated, however. High energy prices discourage irrigation and especially irrigation with groundwater; energy use per acre is 2.87, 6.36, and 13.12 million BTU's for dryland, land irrigated with surface water, and land irrigated with groundwater in the areas selected in Solution I 1990. Most of the irrigation presently occurring in the United States was established under much lower energy prices than those assumed in the model. The neglect of risk may also be an important factor.

The overall pattern of resource use in Solution I is shown in Table 4.2. Water use amounts to 46.6 million acre feet. Fifty-two percent of the water used is groundwater, and 29 percent is groundwater from the Ogallala Aquifer.

Nitrogen fertilizer, including manures, is 18.6 million pounds, or 48 pounds per acre. Nitrogen use on irrigated land averages 90 pounds per acre. Yields are only moderately higher than current yields, except for corn. This is largely a result of trend projections of improved yields.

Table 4.2. Resource use in Solution I 1990

Zone	Non-irrigated land	Land irrigated with Groundwater	Land irrigated with Surface water	Water	Nitrogen fertilizer	Energy
	(1,000 acres)			(1,000 acre feet)	(1,000 pounds)	(billion BTU's[a])
North Ogallala	16,095	3,076	602	7,131	770,877	82,331
Central Ogallala	20,733	1,434	139	2,697	1,466,898	79,257
South Ogallala	6,682	3,133	9	5,028	612,804	64,025
Total Ogallala	43,510	7,643	750	14,856	2,850,579	225,613
Western	124,917	5,343	8,960	31,747	6,961,627	449,329
Eastern	195,066	--	--	--	8,841,462	600,144
Total	363,493	12,986	9,710	46,593	18,653,668	1,275,086

[a]British thermal units.

Energy use in crop production is 1,275,084 billion BTU's[1] of which 56.6 percent represents direct purchases of energy for on-farm use, and the remainder is for agricultural chemicals. An additional 242,964 billion BTU's is needed for transportation of crops between regions. Average energy use is 3.30 million BTU's per acre. The cost of the total amount of energy required is 7.2 billion dollars. Diesel fuel is the most important fuel amounting to 44 percent of all energy costs. Natural gas, because of the importance of nitrogen fertilizer, is close behind, accounting for 41 percent of energy costs, while electricity and LPG represent 10 and 5 percent, respectively.

4.1.2. The Ogallala Zone in Solution I

Agriculture in the Ogallala Zone in the base solution is not too different in structure from current agriculture patterns. Between 10 and 20 percent of endogenous production and resource use is located in the Ogallala Zone. In terms of resources, 13 percent of the land, 15 percent of the nitrogen, and 18 percent of the energy is used in the Ogallala Zone. Eleven percent of production in terms of value is accounted for by the Ogallala Zone. The Ogallala Zone is especially important in the national markets for sorghum, wheat, and cotton, although hay and corn are also dominant crops within the zone. The area is intensively irrigated, and nearly 90 percent of the water used in the area is groundwater.

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[1]Alternatively, 1.275 quads or 1.275×10^{15} British thermal units.

The pattern of irrigation within the Ogallala Zone is similar to current practices. A total of 8.4 million acres is irrigated in the Ogallala Zone (Table 4.2). The North Ogallala shows an expansion in irrigation of 14.5 percent over irrigation in 1974 (reported in Table 1.1). The Central and South Ogallala show a contraction in the area irrigated of 48.2 and 10.6 percent, respectively, over 1974, while irrigation in the entire area is 1.5 million acres less than in 1974.

The area not irrigated because of the decline in the water table is found by comparing the amount of land in the water situations selected in the base run with the amount of land in the same water situations using the 1977 weights rather than the 1990 weights. In total (Table 4.3), 1.05 million acres is depleted, which represents a decline of 11.1 percent in the area that would be irrigated in Solution I if there were no change in the water table. The Central Ogallala shows the largest percentage decline of 15.8 percent, but most of this is because of reduced irrigation in PA 65. For both the North and Central Ogallala, the model selected land in the most

Table 4.3. Effect of the decline of the water table on area irrigated in Solution I 1990

Zone	Area depleted	Income lost	
		Per acre	Total
	(1,000 acres)	(dollars per acre)	(1,000 dollars)
North Ogallala	431	16.81	7,241
Central Ogallala	296	20.20	5,979
South Ogallala	325	93.05	30,243
Total	1,052	41.31	43,463

favorable irrigation situations with depths to water greater than 100 feet being in the marginal range for irrigation. Land class three is generally not irrigated throughout. In the South Ogallala Zone, nearly all water situations are irrigated for land classes one and two. Consequently, nearly all of the area depleted in the South Ogallala is depleted because the aquifer is too thin to support irrigation, while the aquifer is depleted in the North and Central Ogallala because of a combination of the aquifer becoming too thin and the depth to water too great.

The economic consequences are also shown in Table 4.3. The area is, of course, integrated in national commodity markets, so it seems reasonable that the conversion of 1.05 million irrigated acres to dryland out of 386.19 would have little effect on prices. Locally, the effect can be quite large, however, as sales per acre in the Ogallala Zone are 160.77 million dollars less than sales per acre for dryland production in the Ogallala Zone. The total decline in the value of production using the average difference in sales per acre by zone is 169 million dollars. Net farm income also is severely affected. The shadow prices of land in the model represent the returns to land or, alternatively, value of production above purchased inputs represented in the objective function. Consequently, the difference in shadow prices between irrigated land in a particular water situation and dryland represents the difference in net farm income.[1] The loss of income estimates given in Table 4.3 is estimated from the differences

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[1]Not including difference in returns to labor.

in shadow prices per acre. This amounts to 43 million dollars in aggregate with 30 million accounted for in the South Ogallala where the per acre advantages of irrigation over non-irrigated crop production are much greater.

4.2. Effects of Increased Energy Prices in the 1990 Solutions

The model reduces the effects of increased energy prices by shifting to production practices and regions that use less energy. The use of resources which are substitutes for energy is increased, while the use of energy and complementary resources is decreased. Where there are limitations in substitution, as for land and water, the model shows an increase in the value of the resource by higher shadow prices for it. In contrast, the model is not able to show the value of alternate technologies and possible resource substitutions not explicitly built into the model.

A major effect of increased energy prices is to raise crop prices, because the agricultural supply curve shifts up, which should automatically result in reduced demand. Demands, however, are assumed constant because of the limitations of model size and cost. The necessary result, then, is that farm revenue (sales) rises in proportion to prices. Because land is fully utilized and land is an important substitute for energy, the shadow prices of land increase sharply. Land is the residual claimant on the value of production, with other resources receiving predetermined rates of return. Consequently, the returns to land are also interpreted as net farm income exclusive of the returns for operator labor, and the increase in energy prices necessarily leads to an increase in farm income. Decreases in income, therefore, are even more meaningful in that such decreases tend to be underestimated because of fixed demands, and change in relative values are of greater importance.

With all of these reservations, changes in prices and land values are given in Tables 4.4 and 4.5. Crop prices increase 27-49 percent with biggest and smallest increases for oats and cotton, respectively. All land increases in value an average of 69 dollars per acre. The shadow price of irrigated land rises by 80 dollars per acre, but this is a smaller increase in relative terms.

Table 4.4. Effect of the increase in energy prices on crop prices in 1990

Crop	Solution I	Solution II	Percent change
	(dollars per unit)		
Barley	3.16	4.54	43.7
Corn grain	2.95	4.19	42.0
Corn silage	21.52	28.93	34.4
Cotton	258.99	328.60	26.9
Legume hay	68.20	92.66	35.9
Other hay	92.76	129.77	39.9
Oats	3.17	4.72	48.9
Sorghum grain	2.90	4.08	40.7
Sorghum silage	17.37	24.69	42.1
Soybeans	7.03	9.97	41.8
Wheat	5.54	7.99	44.2

Table 4.5. Effect of the increase in energy prices on land values in 1990

Item	Solution I	Solution II	Percent change
	- dollars/acre -		
Irrigated with			
Surface water	162	243	50.0
Groundwater	156	233	49.4
Average	159	239	50.1
Non-irrigated	141	220	56.0
Average all land	142	221	55.6

4.2.1. Effect of the decline in the water table on Solution II 1990

Because a different pattern of water situations is selected in Solution II, the effect on what the solution would have been if the water table were static is somewhat different. In total, the results (Table 4.6) are similar to those for Solution I; 1.07 million acres are lost in aggregate, but income lost per acre is somewhat higher, so the region now loses a total of $53 million in farm income. Again, the South Ogallala is the biggest loser, but in this version especially

Table 4.6. Effect of the decline of the water table on the area irrigated in Solution II 1990

Zone	Area depleted	Income lost: Per acre	Income lost: Total
	(1,000 acres)	(dollars per acre)	(1,000 dollars)
North Ogallala	184	41.42	7,608
Central Ogallala	242	25.63	6,214
South Ogallala	651	61.41	39,979
Total	1,077	49.96	53,801

in terms of the area not irrigated: 651 thousand acres are lost in the South Ogallala Zone alone.

4.2.2. Changes in resource use

The effect of increased energy prices on land use is shown in Table 4.7. Irrigation with surface water increases slightly, while irrigation with groundwater and total irrigation decreases markedly;

Table 4.7. Changes in land use resulting from increased energy prices for 1990

Item	Solution I	Solution II	Percent change
	(1,000 acres)		
Irrigated with			
Surface water	9,710	10,350	6.6
Groundwater	12,985	8,058	-37.9
Total	22,695	18,408	-18.9
Non-irrigated	363,493	367,966	1.2
Total	386,188	386,374	

nearly 5 million acres convert to dryland, with the area irrigated with surface water increasing by 0.6 million acres. Virtually all of the land base is used in Solution I, so it is not possible to increase the total area used appreciably.

The changes in resource use for other resources largely reflect changes in land use, although this is not always the case. For instance, fertilization with nitrogen is also energy intensive, and it might be thought that this would decrease. Total nitrogen actually increases slightly (Table 4.8). Total nitrogen applied is reduced on irrigated land, especially land irrigated with groundwater because of the reduction in the area irrigated. But nitrogen use per acre increases for all categories of land, probably because of the tight land base.

Table 4.8. Effect of increased energy prices on nitrogen fertilizer use for 1990

Item	Solution I	Solution II	Percent change
	(1,000 pounds)		
Irrigated with			
Surface water	815,856	896,836	9.9
Groundwater	1,237,279	829,559	-33.0
Total	2,053,135	1,726,395	-15.9
Non-irrigated	16,600,535	16,953,008	2.1
All land	18,653,648	18,679,392	0.1
	(pound per acre)		
Irrigated with			
Surface water	84.02	86.65	3.1
Groundwater	95.29	102.95	8.0
Total	90.47	93.79	3.7
Non-irrigated	45.67	46.10	0.9
All land	48.30	48.37	0.1

Water use (Table 4.9) mirrors the changes made in the areas irrigated: groundwater use falls off sharply, surface water use increases moderately, with the net effect being a decrease in irrigation water used. Water applications per acre are in the opposite direction of total water, so the adjustments in water use all stem from changes in land use. One might think that water and nitrogen use per acre might decline along the production functions to the reduced water and nitrogen levels included for each basic rotation. But this does not occur generally, because the increase in crop prices

Table 4.9. Effect of increased energy prices on water use for 1990

Item	Solution I	Solution II	Percent change
	(1,000 acre feet)		
Surface water	22,361	23,485	5.0
Groundwater	24,241	15,297	-36.9
Total	46,602	38,782	-16.8
	(acre feet per acre)		
Surface water	2.30	2.27	-1.3
Groundwater	1.87	1.90	1.6
Total	2.05	2.11	2.9

compensates for the increase in energy prices, leaving the same input ratio unchanged.

The result of all of these shifts is that total energy use in crop production decreases by 4.1 percent. Energy use per acre also decreases by 4.1 percent (Table 4.10). Energy use per acre increases slightly for non-irrigated land and land irrigated with surface water but decreases by large amounts for land irrigated with groundwater. This results from a conversion of the most energy intensive irrigation practices to dryland. Energy per acre decreases by an even larger proportion than for irrigation with groundwater because of the change in the proportions of area irrigated by source of water. Other changes in energy use are minor. Energy for agricultural demands increases by 0.5 percent, while energy for machine operation and crop drying decreases 0.3 percent, and energy for transportation decreases 0.6 percent.

Table 4.10. Effect of increased energy prices on energy use for 1990

Land	Solution[a] I	Solution[a] II	Percent change
	(billion BTU's[b])		
Irrigated with			
Surface water	61,767	66,386	7.5
Groundwater	170,373	94,250	-44.7
Total	232,140	160,636	-30.8
Non-irrigated	1,042,352	1,061,954	1.9
All land	1,274,492	1,222,590	-4.1
	(million BTU's[b] per acre)		
Irrigated with			
Surface water	6.36	6.41	0.8
Groundwater	13.12	11.70	-10.9
Total	10.22	8.73	-14.7
Non-irrigated	2.87	2.89	0.6
All land	3.30	3.17	-4.1

[a]Does not include energy for interregional crop transportation but does include energy used in the manufacture of farm chemicals.

[b]British thermal units.

4.2.3. Regional differences

A large portion of the regional differences in the effects of the energy price rise can be traced to altered patterns of land use. The Ogallala Zone has a high proportion of its land irrigated with groundwater, and, in addition, a disproportionately greater share of the area irrigated with groundwater in the Ogallala Zone is converted to dryland as a result of increased energy prices (Table 4.11). Within the Ogallala Zone, the Central Ogallala Zone converts only 21.7 percent of its area to dryland and is compensated by a rise in the area irrigated with surface water. The North Ogallala Zone is most adversely affected in terms of the proportionate decline in area irrigated.

Table 4.11. Changes in land use by region as a result of increased energy prices for 1990

Zone	Irrigated with Groundwater	Irrigated with Surface water	Irrigated with Total	Non-irrigated
		(percent)		
North Ogallala	-66.0	0.0	-55.4	12.6
Central Ogallala	-21.7	56.1	-14.8	1.1
South Ogallala	-44.3	0.0	-44.2	24.2
Total Ogallala	-48.8	10.4	-43.5	8.9
Western	-22.5	6.3	-4.5	0.5
Eastern	--	--	--	0.0
Total	-37.9	6.6	-18.9	1.2

Regional patterns in water, nitrogen, and energy use are largely determined by changes in land use (Table 4.12). Large decreases in water and energy use are evident in the Ogallala Zone. There are especially large declines in nitrogen and energy in the South Ogallala. The Central Ogallala is affected the least, and actually increases nitrogen use by 4.4 percent.

Table 4.12. Changes in water, nitrogen, and energy by region as a result of increased energy prices for 1990

Zone	Water	Nitrogen	Energy[a]
		(percent)	
North Ogallala	-52.6	-4.7	-25.5
Central Ogallala	-13.2	4.4	-1.5
South Ogallala	-50.5	-20.5	-42.8
Total Ogallala	-44.8	-3.4	-22.0
Western	-4.0	2.5	-1.2
Eastern	--	-0.4	0.1
Total	-16.9	0.2	-4.1

[a]Excludes transportation.

An interesting comparison can also be made of the regional effects of the rise of energy prices on purchased inputs and sales. Both purchased inputs and sales are directly related to forward and backward linkages within the local economies. But it is difficult to measure such disparate items except in dollar terms. Constant dollar measures are needed so values may serve as indices of quantities. Table 4.13 shows the change in the values of non-energy and energy inputs valued at prices used in the base solution. All regions except the South Ogallala show an increase in the value of inputs purchased and a

Table 4.13. Change in the value of purchased inputs in constant dollars as a result of increased energy prices for 1990

Zone	Non-energy	Energy	Total
	(1,000 dollars)		
North Ogallala	174,850	-130,760	44,090
Central Ogallala	184,791	-14,267	170,524
South Ogallala	-66,910	-142,356	-209,266
Total Ogallala	292,731	-287,383	5,348
Western	1,342,915	-30,480	1,312,435
Eastern	1,579,558	-62	1,579,496
Total	3,185,215	-317,925	2,867,290
	(percent)		
North Ogallala	14.9	-31.1	2.8
Central Ogallala	13.8	-3.9	10.0
South Ogallala	-9.7	-43.0	-20.5
Total Ogallala	9.1	-25.5	0.1
Western	15.0	-1.3	11.6
Eastern	9.5	--[a]	8.0
Total	11.1	-4.9	8.1

[a]Less than 0.05 percent.

decrease in energy. The South Ogallala Zone shows a decrease in both energy and non-energy inputs. The North and especially the Central Ogallala zones have large areas of non-irrigable land in counties which are not over the Ogallala Aquifer. If the changes in expenditures on these lands are netted out, the gain for the Northern and Central Ogallala in inputs purchased is 3 and 66 million dollars, respectively, with the Ogallala Zone as a whole being deficient by 141 million dollars. The Western Zone is the main beneficiary, although individual producing areas within this zone are doubtlessly disadvantaged.

The effect on sales valued in both flexible and constant prices is shown in Table 4.14. All zones show an increase in sales at the higher prices. At constant Solution I prices, sales in the Western and Eastern zones increase by 1.2 and 0.3 percent, respectively, while sales in the Ogallala Zone decrease by 4.2 percent, indicating a substantial relative decrease in the share of national production. Within the Ogallala Zone, the South Ogallala declines substantially

Table 4.14. Change in the value of production as a result of increased energy prices for 1990

Zone	Changing prices		Constant prices	
	Value	Percent	Value	Percent
	(1,000 dollars)		(1,000 dollars)	
North Ogallala	1,428,789	36.7	-136,118	-3.5
Central Ogallala	1,675,118	40.6	-25,452	-0.6
South Ogallala	274,007	14.9	-343,792	-18.7
Total Ogallala	3,377,914	34.3	-505,362	-5.1
Western	11,552,397	43.3	322,149	1.2
Eastern	21,988,225	42.2	143,788	0.3

(16.1 percent), while the North Ogallala by a considerably lesser amount (3.5 percent), and the decrease by 5.1 percent indicating a substantial relative decrease in the share of national production. Within the Ogallala Zone, the South Ogallala declines substantially, while the North Ogallala by a considerably lesser amount, and the Central Ogallala changes by only a small amount. These results indicate that the economies of the Ogallala Zone are at a competitive disadvantage under increasing energy prices, although with constant demands, rises in prices would be sufficient so that farmers even in these regions would not be adversely affected. We turn now to the effect of reduced demand which would inevitably accompany rising energy prices.

4.3. Effect of Decreased Demand

The model adjusts to decreased demand by adjusting among production methods and regions so that the most costly and marginally profitable activities in the base solution are reduced. The average price of all crops is consequently lower, since prices are determined by marginal costs of production. The value of land and their farm income is also reduced because of the decline in crop prices.

4.3.1. Effect of the decline of the water table on Solution III 1990

The effect of the decline of the water table on local economies is much less drastic for Solution III. The area depleted (Table 4.15) in this solution is 800 thousand acres. This is a smaller area depleted in absolute terms though larger in relative terns than that of Solution I. However, the real difference is in farm income. Under reduced demand, the advantages of irrigation even on the area that

Table 4.15. Effect of the decline of water table on area irrigated in Solution III 1990

Zone	Area depleted	Income lost	
		Per acre	Total
	(1,000 acres)	(dollars per acre)	(1,000 dollars)
North Ogallala	223	18.88	4,216
Central Ogallala	210	9.29	1,949
South Ogallala	367	15.77	5,781
Total	800	14.93	11,946

continues to be irrigated are much lower (only \$14.93 per acre versus \$41.31 per acre in Solution I), so the effect on farm income is to reduce it by 12.9 million rather than the 43.5 million of Solution I. Again the South Ogallala suffers the most, but the effects are quite evenly spread throughout the entire Ogallala in this solution.

4.3.2. Effects of the decrease in demand on resources, prices, and income

The most important effects of the decreased demands are reductions in irrigation and land use. Most of the changes in water, nitrogen, and energy use reflect the changes in land use. Total land use (Table 4.16) is reduced by three percent, or 11.7 million acres. Most (11.2 million) of the reduction is because both the pasture and forest conversion activities do not come into Solution III. The remainder is endogenous cropland not used in the Western Zone. Irrigation with surface water and groundwater both decline; surface water is not a substitute like it was when energy prices increase. Groundwater use shows a dramatic drop (6.9 million acres), while surface water declines by only 0.9 million acres.

Table 4.16. Changes in land use resulting from decreased demand for 1990

Item	Solution I	Solution III	Percent change
	(1,000 acres)		
Irrigated with			
Surface water	9,710	8,807	-9.3
Groundwater	12,985	6,055	-53.4
Total	22,695	14,862	-34.5
Non-irrigated	363,493	359,666	-1.1
Total	386,188	374,529	-3.0

The effect on shadow prices of land is given in Table 4.17. Land prices decline by 25.4 percent. The shadow prices of irrigated land decline less proportionately than non-irrigated land because of the conversion of less profitable irrigated lands to dryland production. Land prices also represent farm income, as explained above. Consequently, farm income, exclusive of returns to labor, decreases by about 25 percent.

Table 4.17. Changes in land values resulting from decreased demand for 1990

Item	Solution I	Solution III	Percent change
	(dollars per acre)		
Irrigated with			
Surface water	162	130	-19.8
Groundwater	156	124	-20.5
Average	159	127	-20.1
Non-irrigated	141	105	-25.5
Average all land	142	106	-25.4

Crop prices decline somewhat less than the prices of land (Table 4.18). Cotton is affected the least, declining by only 8.2 percent. Oats and sorghum grain prices decline by 19.9 and 19.0 percent, respectively, while the rest of the crops are between these extremes.

Table 4.18. Changes in crop prices resulting from decreased demand for 1990

Crop	Solution I	Solution III	Percent change
	(dollars per unit[a])		
Barley	3.16	2.72	-13.9
Corn grain	2.95	2.47	-16.3
Corn silage	21.52	18.78	-12.7
Cotton	258.99	237.64	-8.2
Legume hay	68.20	58.05	-14.9
Other hay	92.76	79.15	-14.7
Oats	3.17	2.54	-19.9
Sorghum grain	2.90	2.35	-19.0
Sorghum silage	17.37	14.30	-17.7
Soybeans	7.03	5.97	-15.1
Wheat	5.54	4.75	-14.3

[a]Units are bushels except for silage and hay, hay being in tons and cotton in bales.

Water and nitrogen use (Tables 4.19 and 4.20) decline in a pattern very similar to the changes in land use. Water and nitrogen use per acre also fall in contrast to the effect of increased energy prices. However, most of the decrease in water use is attributable to decreased irrigation, but most of the decrease in nitrogen use is attributable to decreased nitrogen use per acre.

Table 4.19. Changes in fertilizer used resulting from decreased demand for 1990

Item	Solution I	Solution III	Percent change
	(1,000 pounds)		
Irrigated with			
Surface water	815,856	504,543	-38.1
Groundwater	1,237,279	398,508	-67.8
Total	2,053,138	903,051	-56.0
Non-irrigated	16,600,535	13,366,115	-19.5
All land	18,653,648	14,269,165	-23.5
	(pounds per acre)		
Irrigated with			
Surface water	84.02	57.29	-31.8
Groundwater	95.29	65.81	-30.9
Total	90.47	60.76	-32.8
Non-irrigated	45.67	37.16	-18.6
All land	48.30	38.10	-21.1

Table 4.20. Changes in water use resulting from decreased demand for 1990

Item	Solution I	Solution III	Percent change
	(1,000 acre feet)		
Surface water	22,361	19,534	-12.6
Groundwater	24,241	10,573	-56.4
Total	46,602	30,107	-35.4
	(acre feet per acre)		
Surface water	2.30	2.22	-3.5
Groundwater	1.87	1.75	-6.4
Total	2.05	2.03	-1.0

Energy needed is reduced significantly more than in Solution II. Total energy needs (Table 4.21) are reduced by 273,304 billion BTU's, or 18.0 percent. The largest percentage change is still in energy used for irrigation, but an especially large energy saving is made on energy needed for chemicals; lower demands allow more scope for substitution of land for nitrogen energy. Transportation energy needs also decline by a substantial amount.

Energy demands are reduced proportionately the most for land irrigated with groundwater. The land still irrigated uses less energy; land irrigated with groundwater uses an average of only 9.58 million BTU's per acre in contrast to 13.12 million BTU's per acre in Solution I.

Table 4.21. Changes in energy use resulting from decreased demand for 1990

Item	Solution I	Solution III	Percent change
	(billion BTU's[a])		
Irrigated with			
Surface water	61,767	45,592	-26.2
Groundwater	170,373	57,997	-66.0
Total	232,140	103,589	-55.4
Non-irrigated	1,042,352	940,138	-9.8
All land	1,274,492	1,043,727	-18.1
	(million BTU's[a] per acre)		
Irrigated with			
Surface water	6.36	5.18	-18.6
Groundwater	13.12	9.58	-27.0
Total	10.23	6.97	-31.9
Non-irrigated	2.87	2.61	-9.1
All land	3.30	2.79	-15.5

[a]British thermal units.

Thus, the most marginally irrigated land in the base solution tends also to be the most energy intensive.

4.3.3. Regional differences

Regional effects of the decline in demand on land use are shown in Table 4.22. As can be anticipated from the previous section, there are very large shifts in the Ogallala Zone because of the importance of irrigation with groundwater. The largest shift is for the South Ogallala, which converts 70.2 percent of its groundwater irrigated land to dryland. The North Ogallala converts 51.6 percent to dryland, while the Central Ogallala and Western zones are relatively stable, converting only 27.5 and 23.1 percent, respectively, of their irrigated land to dryland. The Western Zone fares much better than the Ogallala Zone, because irrigation in the Western Zone is not so heavily dependent on groundwater.

Table 4.22. Changes in land use by region resulting from decreased demand for 1990

Zone	Irrigated with			Non-irrigated
	Groundwater	Surface water	Total	
	(percent)			
North Ogallala	-61.7	0.0	-51.6	11.6
Central Ogallala	-25.2	-51.8	-27.5	2.1
South Ogallala	-70.4	0.0	-70.2	34.3
Total Ogallala	-58.4	-9.6	-55.1	10.6
Western	-46.2	-9.3	-23.1	0.7
Eastern	--	--	--	-4.8
Total	-53.4	-9.3	-34.5	-1.1

The change in the use of water, nitrogen, and energy (Table 4.23) largely reflects the change in irrigation patterns in Table 4.22. Water use declines by 55.3 percent in the Ogallala Zone with the largest decline in the South Ogallala and the smallest in the Central Ogallala. In contrast, water use declines by 26.1 percent in the Western Zone. Nitrogen use drops substantially in all regions. Surprisingly, the Eastern Zone is the region with the greatest decline in nitrogen use, both in relative and absolute terms. The Central Ogallala is the most stable, showing a decline of only 10.4 percent.

Table 4.23. Changes in water, nitrogen, and energy by region as a result of decreased demand for 1990

Zone	Water	Nitrogen	Energy[a]
		(percent)	
North Ogallala	-56.5	-26.8	-32.9
Central Ogallala	-27.4	-10.4	-10.5
South Ogallala	-68.5	-26.3	-50.3
Total Ogallala	-55.3	-18.2	-30.0
Western	-26.1	-18.6	-16.4
Eastern	--	-29.1	-15.0
Total	-35.4	-23.5	-18.1

[a]Excludes transportation.

Energy use declines by 50.3 percent in the South Ogallala Zone, largely because of the decline in irrigation. In contrast, energy use declines by only 15.0 and 16.4 percent in the Eastern and Western zones. Again, the Central Ogallala Zone is affected the least with energy declines of only 10.5 percent.

The effect of the decline in demand on economic variables is given in Table 4.24. The decrease in the value of sales in both Solutions I and III prices is given to show the effect on revenue and volume of production, respectively. Revenue declines for the Ogallala are very similar to that of the rest of the nation, but within the Ogallala, the South shows a sharp decrease, while the Central Ogallala gains relatively. This pattern is exaggerated in the value of sales at Solution I prices demonstrating the sharp drop in production in the South Ogallala Zone. This last comparison indicates that forward linkages in the local economies for processing and utilizing agricultural commodities is most affected in the South Ogallala. Similarly, backward linkages in terms of purchased inputs and farm income indicate that the local economy of South Ogallala particularly is adversely affected by decreased demands.

4.4. Extension to 2000

The solutions for 2000 are not reported in as much detail as for 1990. The prime interest in the solutions for 2000 are twofold: to demonstrate the effects of an energy price rise where demands are not so close to productive capacity, and to compare these effects with that of the decline of the water table after the cumulative effects of a further ten years' decline in the water table are included.

4.4.1. Solution I 2000

There are two significant differences in the base solutions for 1990 and 2000 due to the passage of time. During the ten-year interval, yields are assumed to continue to increase at historical rates, but

Table 4.24. Regional declines in sales, purchased inputs, and land values due to decreased demands for 1990

Zone	Value of sales	Value of sales[a] in constant prices	Purchased inputs	Farm income
		(1,000 dollars)		
North Ogallala	905,580	369,077	316,869	587,711
Central Ogallala	674,803	84,614	72,112	602,691
South Ogallala	514,166	313,057	223,804	312,872
Total Ogallala	2,093,549	766,748	612,785	1,503,274
Western	5,391,061	1,692,369	1,179,597	4,211,464
Eastern	11,124,295	3,662,940	2,290,238	8,834,057
Total	18,608,905	5,975,082	4,082,620	14,548,795
		(percent of Solution I)		
North Ogallala	23.2	9.5	19.9	25.5
Central Ogallala	16.4	2.1	4.2	24.9
South Ogallala	27.9	17.0	21.9	61.8
Total Ogallala	21.2	7.8	14.2	27.1
Western	20.2	6.3	10.4	27.4
Eastern	21.4	7.0	11.7	27.2
Total U.S.	21.0	6.7	11.6	27.3

[a]Solution I prices.

demands are assumed to grow only moderately. The amount of land available for irrigation in favorable water situations in the Ogallala Zone continues to decrease because of the falling water table. The effect of the first factor is that productive capacity in 2000 is greater relative to demands than in 1990.

Land utilization in Solution I 2000 is given in Table 4.25. The numbers appear to be similar to those in Table 4.1 for Solution I 1990, but the total amount of irrigation is 16 percent less than in Solution I 1990. More tellingly, crop prices are 13 to 23 percent lower for the 2000 base than for the 1990 base.

Table 4.25. Land use in Solution I 2000[a]

Item	Most productive use	Other use	Total
	(1,000 acres)		
Cropland irrigable with surface water	9,778	4,452	14,230
Cropland irrigable with groundwater	2,632	4,175	6,807
Cropland irrigable from the Ogallala	4,871	13,081	17,952
Private irrigation development	1,255	1,009	2,264
Convertible pasture land	7,471	0	7,471
Convertible forest land	9,897	765	10,662
Non-irrigable cropland	329,913	2,993	332,846

[a]The most productive use is as irrigated cropland for the first four items and as non-irrigated cropland for the last three items.

By 2000, the cumulative effects of the falling water table are making really large impacts on irrigation in the Ogallala Zone. The area depleted in the Ogallala Zone is shown in Table 4.26. The area depleted is more than twice the area depleted for Solution I 1990.

Table 4.26. Effect of the decline of the water table on area irrigated in Solution I 2000

Zone	Area depleted	Income lost	
		Per acre	Total
	(1,000 acres)	(dollars per acre)	(1,000 dollars)
North Ogallala	518	23.81	12,334
Central Ogallala	396	16.02	6,346
South Ogallala	1,187	32.48	39,568
Total	2,101	27.72	58,248

The South Ogallala Zone is particularly hard hit, losing 1.2 million acres of irrigated land with a loss of income to the landowners of 39.6 million dollars. Besides loss of farm income, there would be declines in production and in inputs purchased in these regions. Using the difference in average values of sales for non-irrigated land and land irrigated with groundwater by zone, the loss of sales would amount to 320.5 million dollars for the Ogallala Zone as a whole, with 71 percent of the decline being felt in the South Ogallala. Inputs purchased would decrease by 262.2 million dollars, with 72 percent of this figure applicable to the South Ogallala. The impact on local economies would necessarily be tremendous.

4.4.2. The effect of increased energy prices

The effect of increased energy prices in 2000 is very similar to the results for 1990. Table 4.27 shows that the effect on area irrigated in terms of percentage changes is very similar to those in Table 4.7. The main difference appears to be that irrigation with

Table 4.27. Changes in land use resulting from rising energy prices for 2000

Item	Solution I	Solution II	Percent change
	(1,000 acres)		
Irrigated with			
Surface water	9,778	9,695	-0.8
Groundwater	8,759	5,927	-32.3
Total	18,537	15,622	-15.7
Non-irrigated	372,588	375,690	0.8
All land	391,125	391,312	--[a]

[a]Less than 0.05.

surface water declines marginally instead of increasing by a small amount as it did in 1990. This is readily attributable to lower demands relative to capacity for 2000. Changes in the use of resources reflect the changing patterns in land use. Crop prices (Table 4.28) increase by 26 to 37 percent, a little bit less than the increase in prices for 1990, again attributable to lower demands relative to productive capacity.

Regionally (Table 4.29), the largest shifts in land use are still in the Ogallala Zone because of the continued intensity of irrigation

Table 4.28. Changes in crop prices resulting from increased energy prices for 2000

Crop	Solution I	Solution II	Percent change
Barley	2.58	3.43	32.9
Corn grain	2.45	3.31	35.1
Corn silage	18.55	24.22	30.6
Cotton	206.92	267.13	29.1
Legume hay	55.33	69.58	25.8
Other hay	76.09	100.21	31.7
Oats	2.43	3.29	35.4
Sorghum grain	2.57	3.39	31.9
Sorghum silage	15.10	20.49	35.7
Soybeans	5.63	7.42	31.8
Wheat	4.55	6.24	37.1

Table 4.29. Effect of rising energy prices on land use in 2000

Zone	Irrigated			Non-irrigated
	Groundwater	Surface water	Total	
		(percent)		
North Ogallala	-63.0	0.0	-49.8	8.7
Central Ogallala	-41.8	0.0	-38.9	3.0
South Ogallala	-3.3	0.0	-3.3	2.7
Total Ogallala	-40.9	0.0	-35.9	5.0
Western	-20.2	-0.9	-6.4	0.6
Eastern	--	--	--	--

with groundwater. The large declines are in the North and Central Ogallala, though with the South Ogallala declining in area irrigated with groundwater by only 3.3 percent.

Again, the model understates part of the impacts of rising energy prices in that a resultant decrease in demands is not shown. Consequently, effects on incomes are not estimated. In total, the effect of a doubling of energy prices on the area irrigated in the Ogallala Zone is very similar to the effect of the water table in 2000. Within the Ogallala, the effects are different; the South Ogallala is particularly affected by the falling water table, while the opposite is the case for the North and Central Ogallala.

5. SUMMARY, QUALIFICATIONS, AND IMPLICATIONS

5.1. The Problem and Methodology

The last four decades have seen extensive irrigation development using water derived from the Ogallala Aquifer. Because the amount of groundwater withdrawn greatly exceeds recharge, the water table has been falling throughout the area served by the Ogallala. Previous projections of the economic life of the Ogallala Aquifer have shown irrigated acres to peak during the 70's in the Southern High Plains of Texas, but continued expansion has been projected at least into the last decade of the present century for the areas over the rest of the aquifer. These projections have all focused on a section of the aquifer and have not attempted to gage the effect either of the declining water table or the capacity for irrigation expansion in the region in a framework of interregional competition. This study was undertaken to assess the future competitiveness of irrigation from the Ogallala Aquifer in a framework of high energy prices likely to prevail in the future and to compare the impacts upon the region of increases in energy prices and decreases in demand with the effect of the falling water table.

A regional linear programming model, national in scope with extensive detail on constraints and production possibilities in the area over the Ogallala Aquifer, was used in the analysis. The model minimizes the cost of satisfying a vector of exogenously determined fixed demands for 11 crops: barley, corn, cotton, legume hay, other hay, oats sorghum, silage, soybeans, and wheat. Demands are projected for the target years 1990 and 2000 for 28 market regions. Transportation activities between the major cities of each region incorporate interregional competition. Each of the 28 market regions is composed of one or more of 105 producing areas. Production alternatives within the 105 producing areas are represented by more than 25,000 rotations which simulate producing the crops in various combinations, with varying tillage practices and varying levels of fertilizer and irrigation water utilization. Each rotation represents a different relationship between yields, resource use, and costs that is feasible in a particular producing area. The model determines the prices of all crops as well as all production activities by region. Crop production possibilities within producing areas are different for each of the three zones. Only non-irrigated rotations are included for the producing areas in the Eastern Zone. Dryland rotations and irrigated rotations are included for both the Western and Ogallala zones. Different costs and energy relationships are estimated according to whether the irrigated rotations use surface or groundwater.

The rotations using groundwater in the Ogallala Zone are further disaggregated into eight groundwater situations representing variations in saturated thickness and depths to water with distinct costs estimated for each situation. The first four situations represent saturated thickness of less than 100 feet and depths to water over intervals 0-50, 50-100, 100-200, and 200+ feet. The next four situations represent saturated thickness of more than 100 feet and the same depth to water intervals. The land in the Ogallala Zone is also disaggregated into five land classes according to yield potential and management costs. The eight water situations are used only for land classes one to three as only a small proportion of irrigated land is in classes four and five.

The model is driven by the requirement to satisfy regional demands but is constrained principally by the amount of land available by area that can be used to satisfy these demands. The model assumes that competitive equilibrium and resources receive their market rate of return except land and water, whose returns are determined endogenously.

Irrigation with surface water is restrained by both the amount of surface water available and the amount of land that is able to make use of the water. Irrigation with groundwater is limited only by the amount of land that is estimated to overly viable aquifers. For the Western Zone, the quantity of land irrigable with groundwater is determined as the sum of land already irrigated with groundwater and the amount of cropland that could be developed for groundwater irrigation by 1990. The amount of land irrigable with surface water is estimated as the sum of land historically irrigated with surface water from both private and public sources and future public developments expected to be in use by 1990 for both the Western and Ogallala zones.

The amount of land available in each of the eight water situations in the Ogallala Zone is estimated directly from hydrologic county level maps of the aquifer. The proportion of the county in each water situation and the proportion not over the aquifer is estimated by county. The proportions are projected to the target year iteratively using historical rates of decline of the water table by county.

Proportions for the producing areas for the three land classes are determined as a weighted average of county proportions. The producing area proportions are then multiplied by the total land available in each land class in each producing area giving land constraints by water situation specific to the producing area and land class.

The model is solved under different assumptions concerning energy prices and demands for 1990. In addition, the model is solved recursively in that the rates of decline of the water table are adjusted according to the water withdrawn to establish new sets of land constraints by water situation for the Ogallala Zone for the year 2000. A total of five solutions are compared: three for 1990 and two for 2000. Solutions I and II for 1990 and 2000 differ only in that energy prices are twice as high in Solution II as in Solution I. The solutions are compared to show the impacts of increased energy prices at two different stages in the depletion of the aquifer. Solutions I and III for 1990 differ only in that a lower level of demand is used in Solution III. The solutions are compared to show the effect of changes in demand on agricultural production in the region.

The effect of the declining water table is approximated by using 1977 water situation proportions on the 1990 and 2000 land base to estimate the amount of land converted to non-irrigation. The income and sales lost from this land are also estimated. These results are compared below with the effects of higher energy prices and decreased demand.

5.2. Limitations

The last 20 to 30 years have seen very rapid growth in crop yields. Domestic demands and the land available for agriculture have been fairly stable. The model extrapolates these trends to the target years 1990 and 2000. Without the rapid growth in exports also experienced over this time period, the continued growth in yields would have led to substantial excess capacity in the agricultural sector. The model is sensitive to these trends, and it is necessary to balance demands and production subjectively to obtain an initial solution. To maintain this balance, a large continued increase in exports is assumed.

Intervention in the agricultural sectors has also influenced historical trends. The intervention has taken two forms: investments in research, education, and extension which have led to the development and adoption of more efficient technologies inherent in the trend projections of yields; and income and price maintenance programs designed to benefit the agricultural sector. This last set of programs has functioned to limit supply, taking land out of production. These policies are not included in any solutions, but they would to some extent be a substitute for the level of demands assumed. However, they may differ somewhat in impact in that regional advantage and resource use would be different.

The structure of the model also does not represent the agricultural sector accurately in several important respects. These must be understood to properly appreciate how the results may be interpreted. The full effect of rises in energy prices is not shown explicitly in the model, because demands are fixed within each solution. What is presented as the effect of increased energy prices is actually the effect of a simultaneous increase in energy prices and demand so that quantities demanded do not change. But export demands may be highly elastic,[1] and, therefore, the full effect of an energy price rise would be a combination of the effects of the results given for increased energy prices and decreased demand. The magnitude of the two depends in part on demand elasticities. The full effect of an energy price increase is left to the reader's subjective evaluation. Where decreased demand and increased energy prices reinforce each other in their impact on a variable such as energy used, the results are unambiguous but give only a minimum lower bound of the full effect of an energy price rise. Where they work in opposite directions, such as on crop prices, results tend to be ambiguous.

The model also overestimates resource mobility and ignores the time and costs involved in adjustments to changes in both physical and economic variables. It overlooks the fact that a decrease in production in one region and an increase in another represents a number of individuals in one area leaving the agricultural sector and different individuals elsewhere taking up farming. The model makes such adjustments for very small differences in costs and is also willing to concentrate production regionally.

There are a number of reasons why this representation differs importantly from how the sector operates. Individuals may be unwilling

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[1]Alternatively, the opposite may be the case if the rise in energy prices is global rather than national.

or unable to leave agriculture even though they have to accept a lower income from farming than a competitor elsewhere. Age and skills are important factors limiting exit from the sector. It may also be difficult for production to expand elsewhere if the non-farm production, for example, is not able to handle expansion in production. Established farmers may have better access to capital than beginning farmers, whereas the model does not differentiate. All costs are treated as variable and represent the costs needed to begin operation. Existing cost advantages because of sunk capital and immobile assets such as wells, buildings and structures, and land improvements are ignored.

Risks are also ignored. Irrigation may be preferred despite a small difference in income per acre if it provides a more stable farm income or even better use of family labor. Also, a greater diversity of crops produced than selected by the model would be preferred by the risk averse even if a lower income were involved.

Another important feature of the model is that it is composed of fixed parameters and discrete variables which are approximations of interdependent and continuous real world counterparts. Activities are selected on the basis of mean values estimated independently. Interdependence between coefficients and model results is ignored; irrigation costs, yields, and crop prices are treated as independent, but this may not be the case. Consequently, results are more meaningful at higher levels of aggregation, or, conversely, it is necessary to disaggregate model structure more in an area of particular interest as is done in the Ogallala Zone at a cost of model size and cost.

Data limitations should also be kept in mind. The weights used to disaggregate the Ogallala Zone were derived from data from a great variety of sources. The combination of these data in producing the weights involved a number of key assumptions and a rather ad hoc procedure. Developing other land constraints also involved a number of key assumptions.

The implication of all of the above is that none of the solutions should be treated as or thought of as a prediction or even a projection. Rather, it is the comparison of results that demonstrates the effects of changes in assumptions that is meaningful.

5.3. Results and Conclusions

The major effect of changes in energy prices and demands is to change land use. Changes in the patterns of use of other resources are usually complementary in all solutions to changes in land use. For the three exogenous changes examined, increased energy prices in 1990, decreased demand in 1990, and increased energy prices in 2000, irrigation decreases markedly in every case (Table 5.1). Irrigation with groundwater is particularly sensitive, because it frequently is an energy intensive production practice, and energy prices are assumed to be high throughout.

The effect of increased energy prices in 1990 is to substitute in part surface water and land irrigated with surface water for groundwater and land irrigated with groundwater. Land irrigated with surface water declines in the other two scenarios. This difference results from the relatively high level of demands assumed for

Table 5.1. Summary of changes in land use

Item	Increased energy prices 1990	Decreased demand 1990	Increased energy prices 2000
		(1,000 acres)	
Land irrigated with			
Surface water	+640 (6.6)	-903 (-9.3)	-83 (-0.8)
Groundwater	-5,117 (39.4)	-7,015 (-54.0)	-2,832 (-32.3)
Total	-4,477 (19.7)	-7,918 (-34.9)	-2,915 (-15.7)
Non-irrigated land	4,753 (1.3)	-3,827 (-1.1)	3,102 (0.8)

Solutions I and II 1990. Water and nitrogen (Table 5.2) use per acre also increase slightly for the first scenario for the same reason.

Table 5.2. Summary of changes in resource use

Item	Units	Increased energy prices 1990	Decreased demand 1990	Increased energy prices 2000
Water:				
Total	1,000 acre feet	-8,032	-16,636	-6,165
Per acre	acre feet	0.08	-0.02	-0.03
Nitrogen:				
Total	1,000 pounds	20,040	-4,390,840	-33,237
Per acre	pounds	0.03	-10.21	-0.11
Energy:				
Total	billion BTU	-54,653	-232,617	-28,306
Per acre	million BTU	-0.14	-0.52	-0.07

Water use drops dramatically for all three scenarios with the decline due to decreased demand twice as large as that for increased energy prices. Nitrogen use is quite stable for the two increased energy price scenarios but declines by 23.5 percent with the decrease in demand with most of the reduction accomplished through reductions in nitrogen applied per acre on irrigated and non-irrigated land. The difference is because crop prices negate the effect of increased energy prices in selecting the yield fertilizer ratio, but decreased crop prices in the decreased demand scenario lowers crop prices leading to a movement along the yield surface.

Crop prices increase 26 to 49 and 26 to 37 percent for the increase in energy prices in 1990 and 2000, but decline 8 to 19 percent for the decreased demand scenario. The value of land reflects changes in crop prices and land's value as a substitute for other purchased inputs, and, therefore, increases sharply with increased energy prices and declines with decreased demand.

Energy use declines in all scenarios, but the decline is most dramatic for decreased demand. In this scenario, energy needed for irrigation, chemicals, and crop transportation all decline substantially, and energy used for machine operation and crop drying declines by five percent. With increased energy prices, energy for irrigation drops substantially but energy needed for other uses shows little change. It is evident from the results in Tables 5.1 and 5.2 that the full effect of increased energy prices is to greatly reduce the area that can be profitably irrigated with groundwater. The use of water, nitrogen, and energy would all be cut back. Non-irrigated land, crop prices, and land values may all increase or decrease because of the full effect of rising energy prices; the model does not give definitive answers for these variables. It is quite clear, however, that much of the land irrigated with groundwater is marginally profitable.

There are only minor regional differences in the overall pattern in complementary shifts in resource use except in terms of relative magnitude. The relative magnitudes of the shifts in land use are greatest in the Ogallala Zone where there is extensive irrigation with groundwater. The shifts in land use in the Eastern and Western zones are quite small in relative terms although there may be important localized changes within these zones not analyzed here.

There are, however, considerable differences within the Ogallala Zone (Table 5.3). The Central Ogallala shows the largest reduction in area irrigated compared with 1974. However, the Central Ogallala is least affected by rising energy prices and falling demand both in absolute and relative terms. Both the South and North Ogallala show large declines in area irrigated because of increased energy prices and decreased demand in 1990. The economic impacts, however, are much greater for the South Ogallala. In contrast, land use in the South Ogallala is barely affected by energy price rises in 2000, in part because less marginal areas are irrigated in the 2000 base solution.

The area not irrigated in the Ogallala Zone because of the decline in the water table is partly an economic phenomenon as it depends upon water situations that are profitable to irrigate. This in turn depends on such factors as energy prices and demands. The areas depleted and

Table 5.3. Summary of effect of change in energy price rises and declines in demand on production in Ogallala Zone

Item	Increased energy prices 1990	Decreased demand 1990	Increased energy prices 2000
		(1,000 acres)	
Area withdrawn from irrigation:			
North Ogallala	2,030	1,897	1,431
Central Ogallala	233	433	622
South Ogallala	1,667	2,293	45
Total	3,930	4,623	2,098
		(1,000 dollars)	
Decline in value of production:[a]			
North Ogallala	136,118	369,077	92,428
Central Ogallala	25,452	84,614	46,500
South Ogallala	343,792	313,057	18,795
Total	505,362	766,748	157,723
		(1,000 dollars)	
Decline in value of purchased inputs:[a]			
North Ogallala	-44,090	316,869	-37,083
Central Ogallala	-170,524	72,112	-130,968
South Ogallala	209,266	223,804	-41,251
Total	-5,348	612,785	-209,302

[a]In constant prices.

economic consequences for three solutions are summarized in Table 5.4. The data in Table 5.4 are most directly comparable to that presented in Table 5.3 for the effects of increased energy prices in 1990, decreased demand in 1990, and increased energy prices in 2000.

The area depleted may be lost, because the saturated thickness of the aquifer is too thin to support irrigation, or the pumping lift is sufficiently great to make irrigation non-profitable because of the water table's decline over the periods 1977-1990 and 1990-2000.

Table 5.4. Summary of effects of water table decline on production in Ogallala Zone

Item	Solution II 1990	Solution III 1990	Solution II 2000
		(1,000 acres)	
Area depleted:			
North Ogallala	184	223	332
Central Ogallala	242	210	284
South Ogallala	651	367	1,173
Total	1,077	800	1,790
		(1,000 dollars)	
Decline in value of production:			
North Ogallala	50,674	21,785	40,570
Central Ogallala	46,827	24,921	46,414
South Ogallala	198,822	47,985	277,262
Total	296,323	94,691	364,246
		(1,000 dollars)	
Decline in value of purchased inputs:			
North Ogallala	43,066	17,569	32,849
Central Ogallala	40,613	22,972	42,951
South Ogallala	158,843	42,204	249,217
Total	244,522	82,745	325,017
		(1,000 dollars)	
Income lost:			
North Ogallala	7,608	4,216	7,721
Central Ogallala	6,214	1,949	3,463
South Ogallala	39,979	5,781	28,045
Total	53,801	11,966	39,229

The area depleted by 1990 is 1.08 and 0.80 million acres for the two 1990 solutions given in Table 5.4. The lesser amount is for Solution III, which selected fewer water situations as economically profitable to irrigate in the South Ogallala.

The income lost is much greater in the South Ogallala, because the benefits from irrigating are greater there. Irrigation has a relatively larger advantage over dryland production in the South Ogallala. The economic benefits also are influenced greatly by the assumptions inherent in each solution. High energy prices and demands cause high crop prices which raise the average per acre value of the area depleted in the South Ogallala to 61.41 dollars. Lower prices in Solution III 1990 reduce the per acre value of the area irrigated to 15.77 dollars. The additional area depleted in the period 1990-2000 is also especially severe in the South Ogallala.

There are important differences over time with respect to the effect of the decline of the water table, energy prices, and demand on agricultural production in the Ogallala Zone. A comparison of Tables 5.3 and 5.4 is useful in demonstrating these differences. In 1990, the effects of increased energy prices and decreased demand are both much more deleterious to irrigation in the Ogallala Zone than the decline in the water table. But by 2000, the cumulative effects of the water table decline assert itself especially in the South Ogallala. The North and Central Ogallala remain more important than increased energy prices in 2000. The North and Central Ogallala would be forced to balance withdrawals with recharge with a greater amount of water remaining in storage because of these economic phenomena and the earlier development in the southern portion of the aquifer.

When evaluating these results, it should also be kept in mind that qualitatively different phenomena are being compared. The decrease in irrigation because of the decline of the water table is a certain, slow inexorable process that demands attention. A similar phenomenon in Arizona eventually led to the Central Arizona Project. Research on methods of making more efficient use of Ogallala water would be an appropriate political response. Techniques which conserve both water and energy should be a high priority. Alternatives of this type include development of more water efficient crop varieties, irrigation scheduling, reduction in irrigation losses from conventional water distribution methods, adoption of drip or trickle irrigation systems, and the development of alternate energy sources for irrigation such as solar and wind.

It should also be recalled that the commonality in water rights is largely accepted by the institutions governing the use of Ogallala water, encouraging overuse of the water. It would be useful to estimate how important a factor this is in determining withdrawals and, if important, attempt to develop the appropriate means of controlling this problem. The present piecemeal approach using voluntary conservation districts seems inadequate. It is ironic that there are at least three publicly funded projects evaluating the import of water to the Ogallala Zone, but no attempts are made to control misuse of the water from the aquifer.

Finally, the certainty of the declining water table should not obscure the vulnerability of the region in an economy with high energy prices. Citizens in the area may find it more difficult to find political support with their special problems with energy prices. In the short term, rising energy costs will be much more devastating to farmers in the region than the falling water table. Research on methods of irrigation that are less energy intensive and alternate energy sources would be an important response. A decline of the relative importance of the area as a crop production region should be anticipated throughout the zone and appropriate policies to facilitate the change developed.

6. REFERENCES

Arrow, Kenneth S., and Mordecai Kurz
1970 Public investment, the rate return, and optimal fiscal policy. Baltimore, Maryland: Johns Hopkins Press.

Bekure, Solomon
1971 An economic analysis of the intertemporal allocation of ground water in the Central Ogallala Formation. Unpublished Ph.D. dissertation, Oklahoma State University, Stillwater, Oklahoma.

Bellman, Richard
1957 Dynamic programming. Princeton, New Jersey: Princeton University Press.

Boetcher, Arnold J.
1966 Ground-water development in the High Plains of Colorado. United States Geological Survey, Water Supply Paper 1819-I.

Burt, Oscar R., and Ronald G. Cummings
1977 Natural resource management, the steady state, and approximately optimal decision rules. Land Economics 53, No. 1:1-22.

Burt, O. R., R. G. Cummings, and J. W. McFarland
1977 Defining upper limits to groundwater development in the arid west. American Journal of Agricultural Economics 59, No. 5: 943-947.

Condra, Gary D., and Ronald D. Lacewell
1975 Effect of alternate product and input prices on demand for irrigation water: Texas High Plains. The Texas Agricultural Experiment Station, Department of Agricultural Economics, DIR 75-1, SP-6.

Condra, Gary D., Ronald D. Lacewell, J. Michael Sprott, and B. Michael Adams
1975 A model for estimating demand for irrigation water on the Texas High Plains. Texas A & M University, Texas Water Resources Institute (College Station, Texas), TR-68.

Coomer, J. M.
1978 Projected irrigation adjustments to increasing natural gas prices in the Texas High Plains. Unpublished M. Sc. Thesis, Texas Tech. University, Lubbock, Texas.

Cronin, J. G.
1969 Ground water in the Ogallala Formation in the Southern High Plains of Texas and New Mexico. United States Geological Survey, Hydrologic Investigation Atlas HA-330.

Department of Agriculture
1972-78 Agriculture Prices Annual Summary. PR 1-3 (72-78).

Department of Agriculture
1975 Agricultural Prices. PR 1 (6-75).

Department of Agriculture
1979 Agriculture Prices. PR 1 (3-79), (6-79), (9-79), and (12-79).

Department of Agriculture Soil Conservation Service
1976 Crop consumptive irrigation requirements and irrigation efficiency coefficients for the United States.

Department of Commerce Bureau of the Census
1961 1959 Census of Agriculture: Volume I, Parts 1-48.

Department of Commerce Bureau of the Census
1967 1964 Census of Agriculture: Volume I, Parts 20, 21, 36, 37, 41, and 42.

Department of Commerce Bureau of the Census
1972 1969 Census of Agriculture: Volume I, Parts 20, 21, 36, 37, 41, and 42.

Department of Commerce Bureau of the Census
1973 1969 Census of Agriculture: Volume IV, irrigation.

Department of Commerce Bureau of the Census
1977 1974 Census of Agriculture: Volume I, Parts 1-50.

Department of the Interior
1968 Progress report on west Texas and eastern New Mexico import project investigations. Amarillo, Texas.

Department of the Interior
1973 West Texas and eastern New Mexico import project, reconnaissance report. Washington, D.C.

Department of the Interior
1977 Ground-water manual, a guide for the investigation, and management of ground-water resources. Washington, D.C.

Department of Labor
1974-78 Wholesale price and price indexes. Annual Supplements, 1973-77.

Department of Labor
1979 Producer price and price indexes. Annual Supplement, 1978.

Department of Transportation
1976 Highway Statistics 1975. Report No. FHWA-HP-HS-75.

Dewsnup, Richard L., and Dallin W. Jenson (eds.)
1973 A summary-digest of state water land. Arlington, Virginia: National Water Commission.

Dvoskin, Dan, and Earl O. Heady
1976 Energy requirements of irrigated crops in the western United States. Iowa State University Center for Agricultural and Rural Development (Ames, Iowa), Miscellaneous Report.

Dvoskin, Dan, Earl O. Heady, and Burton C. English
1978 Energy use in U.S. agriculture: an evaluation of national and regional impacts from alternative energy. Iowa State University Center for Agricultural and Rural Development (Ames, Iowa), CARD Report 78.

Edward E. Johnson, Inc.
1966 Groundwater and wells. St. Paul, Minnesota: Edward E. Johnson, Inc.

Ekholm, Arthur L., Dean F. Schreiner, Vernon R. Eidman, and Gerald A. Doekson
1976 Adjustments due to a declining groundwater supply: High Plains of Oklahoma and Texas. Oklahoma Agricultural Experiment Station, Bulletin T-142.

English, Burton C., and Dan Dvoskin
1977 National and regional water production functions reflecting weather conditions. Iowa State University Center for Agricultural and Rural Development (Ames, Iowa), Miscellaneous Report.

Governor's Task Force on Water Resources
1977 Interim report of the governor's task force on water resources. Office of the Governor, Topeka, Kansas.

Ground Water Conservation District No. 2
ca. 1967 Rules of north plains Ground Water Conservation District No. 2, North of the Canadian River. Ground Water Conservation District No. 2, Dumas, Texas.

Gutentag, Edwin D., and Lloyd E. Stullken
1976 Ground-water resources of Land and Scott counties, Western Kansas. Kansas Geological Survey, Irrigation Series No. 1.

Hanson, Marlin Lewis
1966 Law and the economics of ground water mining in a pump irrigated area of Nebraska. Unpublished Ph.D. dissertation, University of Nebraska, Lincoln, Nebraska.

High Plains Associates
1979 Interim report, six-state High Plains - Ogallala Aquifer area study. Austin, Texas: High Plains Associates.

Hughes, William F., and Wyatte L. Harman
1969 Projected economic life of water resources, subdivision 1, High Plains Underground Water Reservoir. Texas Agricultural Experiment Station, Monograph 6.

Huisman, L.
1972 Groundwater recovery. London, United Kingdom: The Macmillan Press, Ltd.

Intrilligator, Michael D.
1971 Mathematical optimization and economic theory. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

Irrigation Journal
1978 1978 irrigation survey. Irrigation Journal 28, No. 6: 16-22.

Jenkins, Edward D., and Marilyn E. Pabst
1975 Water development for irrigation in northwestern Kansas. United States Geological Survey (Lawrence, Kansas), Open File Report 4-75.

Kansas State Board of Agriculture
1978 61st annual report and farm facts. Kansas State Board of Agriculture (Topeka, Kansas).

Kletke, Darrel D., Thomas R. Harris, and Harry P. Mapp, Jr.
1978 Irrigation cost program users reference manual. Oklahoma Agricultural Experiment Station, Research Report P-770.

Lacewell, Ronald D., Gary D. Condra, Daniel C. Hardin, Luis Zazaleta, and James A. Petty
1978 The impact of energy shortage and cost on irrigation for the High Plains and Trans Pecos Regions of Texas. Texas A & M University, Texas Water Resources Institute (College Station, Texas), Technical Report No. 98.

Lacewell, Ronald D., Lonnie L. Jones, and James E. Osborn
1976 Adjustments due to a declining groundwater supply: High Plains of northern Texas and western Oklahoma. Texas A & M University, Texas Water Resources Institute (College Station, Texas), Technical Report No. 74.

Lansford, Robert R., William Brutsaent, Bobby J. Creel, Adan Flores, and Walter Loo
1974 Water resources evaluation of the southern High Plains of New Mexico. New Mexico State University, New Mexico Water Resources Research Institute (Las Cruces, New Mexico), WRRI Report No. 044.

Lappala, Eric G.
1978 Quantitative hydrogeology of the Upper Republican Natural Resource District, southwest Nebraska. United States Geological Survey, Water-Resources Investigations 78-38.

McClain, Thomas J., Edward D. Jenkins, Katherine M. Keene, and Marilyn E. Pabst
1975 Water resources of Gove, Logan, and Wallace counties, west-central Kansas. United States Geological Survey, Hydrological Investigations Atlas HA-521.

McCullick, Joe Jack
1970 The economic impact of irrigation on selected southwestern Kansas counties: an input-output approach. Unpublished Ph.D. dissertation, Kansas State University, Manhattan, Kansas.

McGuinness, C. L.
1964 Generalized map showing annual runoff and productive aquifers in the conterminous United States. United States Geological Survey, Hydrological Investigations Atlas HA-194.

Mapp, Harry P., Jr., and Craig L. Dobbins
1977 The impact of increased energy costs on water use and agricultural output in the Oklahoma Panhandle. Oklahoma Agricultural Experiment Station, Research Report P-755.

Mapp, Harry P., Jr., and Vernon R. Eidman
1976 An economic analysis of regulating water-use in the Central Ogallala Formation. Oklahoma Agricultural Experiment Station, Technical Bulletin T-141.

Meister, Anton D., and Kenneth J. Nicol
1975 A documentation of the national water assessment model of regional agricultural production, land and water use, and environmental interaction. Iowa State University Center for Agricultural and Rural Development (Ames, Iowa), Miscellaneous Report.

Morton, R. B., and R. L. Goemaat
1972 Reconnaissance of the water resources of Beaver County, Oklahoma. United States Geological Survey, Hydrological Investigations Atlas HA-450.

Muller, Daniel A., and Robert D. Price
1979 Ground-water availability in Texas, estimates and projections through 2030. Texas Department of Water Resources Report 238.

Osborn, James E.
1973 Economic effects of an exhaustible irrigation supply: Texas High Plains. Southern Journal of Agriculture Economics, 5, No. 1:135-139.

Osborn, James E., and Jock D. Mason
1974 The economic impact of the crop and feedlot sectors on the Texas High Plains economy. Texas Tech University Department of Agricultural Economics, Technical Report T-1-118.

Osborn, J. E., and J. R. Harris
1973 Economic analysis: interindustry effects of a declining groundwater supply, southern High Plains of Texas. Texas Agricultural Experiment Station, B-1134.

Osborn, James E., and William C. McCray
1972 An interindustry analysis of the Texas High Plains - part I. Texas Tech University Department of Agricultural Economics (Lubbock, Texas), Technical Publication T-1-102.

Pearl, Richard Howard, Robert S. Roberts, Katherine M. Keene, and Thomas J. McClain
1972 Water resources of northwestern Kansas. United States Geological Survey, Hydrologic Investigations Atlas HA-429.

Rohdy, D. D., D. B. Tanner, and P. W. Barkley
1971 Secondary economic effects of irrigation on the Colorado High Plains. Colorado Agricultural Experiment Station, Bulletin 545S.

Sapik, D. B., and R. L. Goemaat
1973 Reconnaissance of the ground-water resources of Cimarron County, Oklahoma. United States Geological Survey, Hydrological Investigations Atlas HA-373.

Short, Cameron, and Anthony F. Turhollow, Jr.
ca 1981 Irrigation in the CARD programming models. Iowa State University Center for Agricultural and Rural Development (Ames, Iowa), Miscellaneous Report.

Slagle, Stephen E., and Edward C. Weakly
1976 Ground-water resources of Greeley and Wichita counties, western Kansas. Kansas Geological Survey (Lawrence, Kansas), Irrigation Series No. 2.

Sloggett, Gordon
1977 Mining the Ogallala Aquifer: state and local efforts in groundwater management. Oklahoma Agricultural Experiment Station, Research Report P-761.

Stoecker, Arthur
1974 A quadratic programming model of U.S. agriculture in 1980: theory and application. Unpublished Ph.D. dissertation, Iowa State University, Ames, Iowa.

Svoboda, Gerald R.
1978 Laws, rules, and regulations pertaining to groundwater in Nebraska. University of Nebraska, Institute of Agriculture and Natural Resources (Lincoln, Nebraska).

University of Nebraska Conservation and Survey Division
1966 Ground water atlas of Nebraska. Lincoln, Nebraska.

Wood, P. R., and D. L. Hart, Jr.
1967 Availability of ground water in Texas County, Oklahoma. United States Geological Survey, Hydrological Investigations Atlas HA-250.

Wyatt, A. Wayne, Ann E. Bell, and Shelly Morrison
1977 Analytical study of the Ogallala Aquifer in Briscoe County, Texas, Texas Water Development Board (Austin, Texas), Report 212.

Young, Kenneth B.
1977 The impact of rising natural gas prices on agriculture in the Texas High Plains. State of Texas Governor's Energy Advisory Council (Austin, Texas), Technical Report 77-107.

7. APPENDIX A: ESTIMATION OF WATER SITUATION WEIGHTS FOR IRRIGATION FROM THE OGALLALA AQUIFER

Figure A.1 shows all of the counties in the seven Ogallala PA's that are assumed in this study to draw upon the Ogallala Aquifer for at least part of the water that the county needs for irrigation. Each of the PA's is subdivided into eight water situations defined in terms of depth to water and saturated thickness of the aquifer. The saturated thickness intervals are 0-100 and 100+ feet, while the depth to water intervals are 0-50, 50-100, 100-200, and 200+ feet. Different irrigation costs and energy coefficients per acre foot of water pumped are used for each water situation. The amount of land in each situation limits irrigation. This section describes how the amount of land in each situation is estimated.

The amount of land in each situation is estimated from a set of weights developed by county for intersections of depth to water and saturated thickness intervals. The weights were developed from maps of the aquifer showing contours of these intervals. The maps were available from a number of authors, as shown in Table A.1, and each had its own peculiarities, so different methods were used in estimating the weights. Region A, for example, consists of all but three of the Nebraska counties for which weights were calculated. The reference year, for which the data from each source are applicable, is shown in Table A.1. For region A, the reference year was not clearly stated but probably refers to 1965 or earlier, but 1965 is assumed. From some sources, contours of equal saturated thicknesses and equal depths

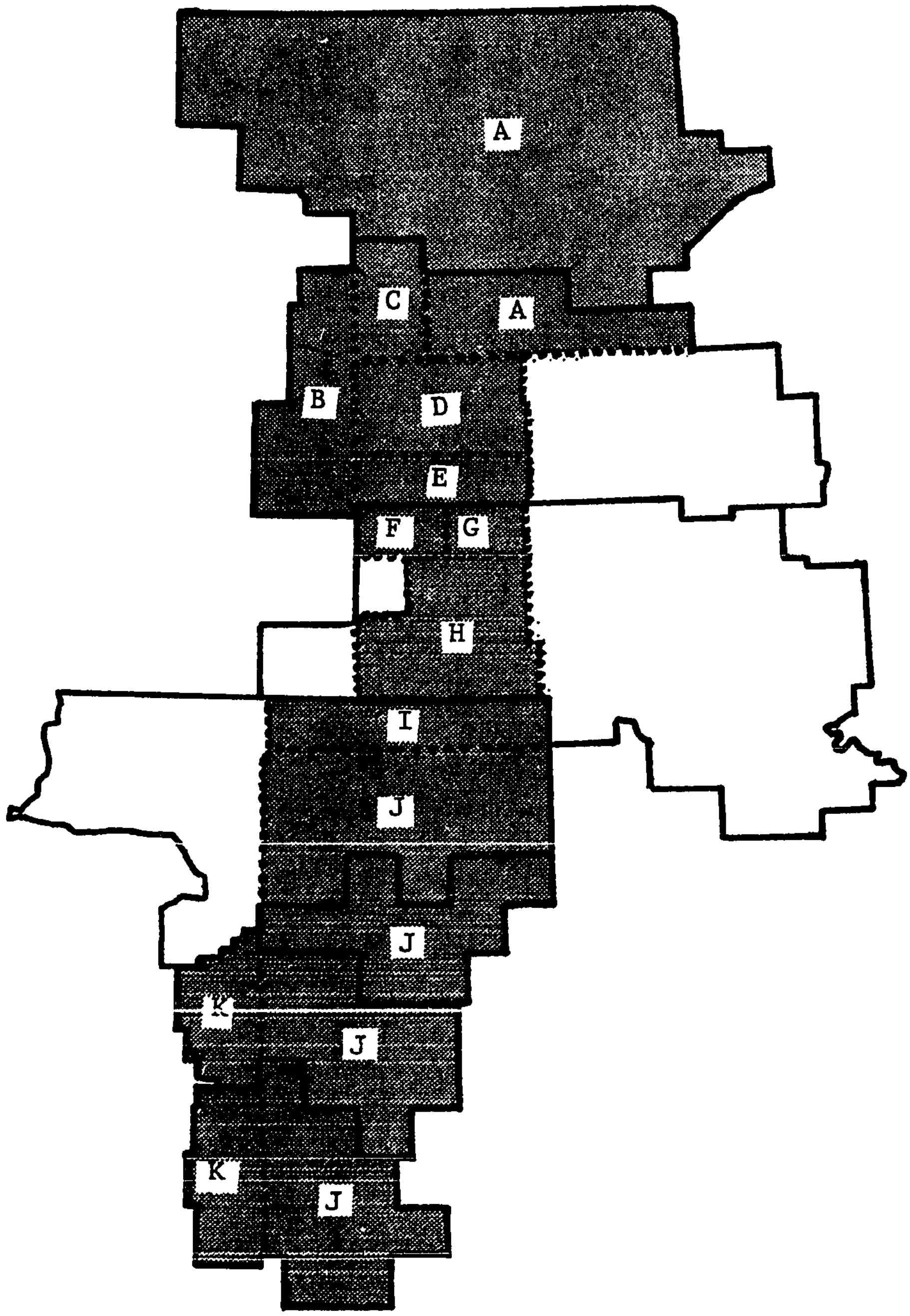

Figure A.1. Area within the Ogallala Zone for which water situation proportions are estimated

Table A.1. Summary of data used to generate water-resource situation weights by source

Region	Source	Reference year	Saturated thickness intervals (feet)	Depth to water intervals (feet)
A	University of Nebraska (1966)	1965	0-20,20-100,100-200,etc.	0-100,100-200,etc.
B	Boetcher (1966)	1963	50	50
C	Lappala (1978)	1975	0-50,50-100,100-200,etc.	0-20,20-50,50-150,150+
D	Pearl _et al_. (1972)	1977	0-50,50-100,100-200,etc.	0-50,50-100,100-200,etc.
E	McClain _et al_. (1975)	1970	50	50
F	Slagle and Weakley (1976)	1972	0-20,20-40,40-80,etc.	none
G	Gutentag and Stullken (1976)	1973	0-40,40-80,etc.	none
H	Gutentag, Labmeyer, and Slagle[a]	1975	50	none
I	Wood and Hart (1967), Sapik and Goemaat (1973), and Morton and Goemaat (1972)	1966-68	50	50
J	Texas Water Development Board, Austin, Texas	1974	50	50
K	Cronin (1969)	1967	50	none

[a]Personal communication, Edwin D. Gutentag, U.S. Geological Survey, Lawrence, Kansas.

to water are given on a single map. The intervals between contours represent water resource situations. Each water-resource situation is defined by the intersection and saturated thickness interval with each depth to water interval.

The area encompassed by the intersection of each saturated thickness interval with each depth to water interval is measured with a polar planimeter or in a few instances by "counting dots." Each area is then divided by the area of the county found by adding the individually measured areas. The final result is a matrix of weights, each weight representing the proportion of the area of each county that falls in each water-resource situation. An example is given in Table A.2. This method of estimating weights is followed for data from all sources.

Table A.2. Example: weights for water resource situations calculated for Cheyenne County, Kansas

Saturated thickness	Depth to water 0'-50'	50'-100'	100'-200'	200'-300'
0'-50'	.1731	.0983	.0783	.0454
50'-100'	.0043	.0353	.1166	.0439
100'-200'	.0069	.0305	.2564	.1065
200'-300'	--	.0015	.0030	--

Data from most sources are not found on a single map. For regions B, C, and I, transparencies are prepared from one map and overlayed on a second map. Region A was a special problem in that not only are saturated thickness and depth to water contours on separate maps, but the maps are very large scale. These maps were enlarged by projecting them onto a screen and tracing the contours overlying saturated thickness contours and depth to water contours. Regions F, G, and H, which comprise all of the Ogallala area in PA 63 and region K, also presented special problems in that maps of saturated thickness contours only are available. Each of these saturated thickness intervals was subdivided into depth to water intervals in the same ratio as the comparable saturated thickness intervals in the adjacent counties. Some of the most reliable data were found for region J, which consists of the High Plains of Texas. Texas is far ahead of other states in detailed ongoing monitoring of ground water. A large network of observation wells has been established and data computerized so that computer generated maps of each county are available. A 45-county set of saturated thickness maps and a 45-county set of pumping lift maps with contours in 25-foot intervals are used for Texas. These are traced at 50-foot intervals so that the areas of intersection of saturated thickness and pumping lifts could be estimated. Pumping lift consists of depth to water plus drawdown. The drawdowns assumed are given in formulas which depend upon saturated thickness, so it is necessary to convert the intervals back to depths to water.

The raw weights are used in a PL1 program designed to adjust them to the base year 1990 and to eight common intervals of depth to water and saturated thickness. The adjustment throughout assumes that land is evenly distributed within the range represented by a water-resource situation. Although this is almost certainly not the case within any given range, counties are eventually aggregated into PA's, so errors introduced by this assumption cancel out. The program adjusts each weight iteratively so that a portion of the weight is reassigned to a lower saturated thickness interval and a higher depth to water interval. The proportion reassigned is determined by the rate of decline of the saturated thickness interval as shown in Equation A.1:

$$W_{i,j,t+1} = (1 - D_i)^2 W_{i,j,t} + \tfrac{1}{2}(D_{i+1}(1 - D_{i+1}) + D_{i+1} (1 - D_i)) W_{i+1,j,t} + D_i (1 - D_i) W_{i,j-1,t} + \tfrac{1}{2}(D_i D_{i+1} + D^2_{i+1}) W_{i+1,j-1,t} \qquad (A.1)$$

where

$i = 1, 2, \ldots$ for the saturated thickness interval,

$j = 1, 2, \ldots$ for the depth to water interval,

$t = 1, 2, \ldots$ for the year,

$W_{i,j,t}$ is a county weight for saturated thickness interval i, depth to water interval j, and year t, and

D_i is the proportional change interval boundaries defined as the rate of decline of the aquifer in feet per year divided by the width of the saturated thickness interval.

Each weight for each county is iteratively adjusted the appropriate number of times so that all weights represent a base year. The rates of decline used for counties in Texas are for 20-foot intervals obtained from the Texas Department of Water Resources.[1] Rates of decline for other counties are simply county averages assumed to hold over all 20-foot intervals estimated from a variety of sources.

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[1]Personal communication. December, 1979. Much of the data are available in a series of studies by Wyatt, Bell, and Morrison (1977).

The county weights are simultaneously aggregated into the eight water situation intervals and averaged to PA level by land class for land classes one to three. Nearly all irrigated land in the seven PA's in the Ogallala Zone are in land classes one to three, so land in land classes four and five is not disaggregated into water situations. A portion of the land in the 0-100 foot saturated thickness interval is assumed non-irrigable because the aquifer would be so thin as to preclude sufficient well yields for irrigation. The proportion assumed non-irrigable is 20 percent for all areas in PA's 55, 58, 65, 67, and the northern three counties in PA 72, and 30 percent for the rest of the area. The weights used to average the county weights to PA level are the proportion of non-irrigated and irrigated (minus surface irrigated land) land by land class and PA that is in the county estimated from the 1967 Conservation Needs Inventory. Thus, the final weights should apply to all irrigable cropland and not just cropland currently irrigated. The weights can then be multiplied by the amount of non-irrigable and irrigable land (excluding surface irrigable) included in the counties in the shaded area.

The weights do not add to one, because the original weights add to less than one for counties which lie on the boundary of the aquifer and because of the portions assumed non-irrigable because the aquifer is too thin. The difference between the sum of the weights and one is the proportion of the PA in the shaded area that is non-irrigable by land class. This is added to the non-irrigable area in the non-shaded counties in Figure A.1 to give the dryland constraints in Table 3.1.

Final PA weights for three years are given in Tables A.3 to A.5. The weights for 1977 and 1990 are estimated as explained above. The weights for 2000 are calculated as above except that the rates of decline are modified according to the water the model elects to withdraw from the aquifer according to Solution I 1990. Water withdrawn in the model solution was 137, 55, and 106 percent of the water withdrawn in 1974 in the Northern, Central, and South Ogallala, respectively. Therefore, the decline rates were modified proportionately for the ten iterations between 1990 and 2000.

Table A.3. Weights for water situations for 1977

Producing area	Land class	Saturated thickness: 0-100 feet depth to water (feet)				Saturated thickness: 100+ feet depth to water (feet)			
		0-50	50-100	100-200	200+	0-50	50-100	100-200	200+
55	1	.068	.068	.082	.010	.177	.177	.273	.082
	2	.068	.068	.091	.017	.179	.179	.288	.085
	3	.062	.062	.079	.019	.178	.178	.259	.075
58	1	.059	.059	.207	.056	.023	.023	.195	.065
	2	.062	.062	.194	.064	.031	.031	.170	.080
	3	.056	.056	.160	.054	.034	.034	.174	.118
63	1	.037	.088	.126	.030	.038	.125	.257	.044
	2	.038	.088	.086	.016	.041	.123	.235	.037
	3	.032	.086	.090	.019	.034	.120	.250	.038
65	2	.014	.014	.028	.051	.032	.076	.215	.339
	3	.045	.036	.072	.067	.053	.123	.254	.231
67	1	.069	.154	.244	.105	.003	.006	.049	.040
	2	.027	.098	.236	.176	.002	.008	.088	.094
	3	.036	.110	.260	.197	.003	.009	.098	.107
72	1	.038	.068	.131	.089	.026	.045	.184	.208
	2	.039	.069	.148	.101	.015	.025	.180	.154
	3	.067	.095	.160	.066	.026	.045	.116	.080
74	2	.104	.141	.163	.020	.029	.049	.021	.001
	3	.117	.170	.194	.023	.022	.039	.017	.001

Table A.4. Weights for water situations for 1990

Producing area	Land class	Saturated thickness: 0-100 feet depth to water (feet)				Saturated thickness: 100+ feet depth to water (feet)			
		0-50	50-100	100-200	200+	0-50	50-100	100-200	200+
55	1	.051	.051	.109	.024	.120	.120	.284	.120
	2	.054	.054	.118	.035	.128	.128	.285	.118
	3	.050	.050	.099	.033	.134	.134	.261	.106
58	1	.048	.048	.197	.094	.017	.017	.157	.086
	2	.052	.052	.185	.091	.025	.025	.146	.096
	3	.048	.048	.159	.080	.027	.027	.148	.136
63	1	.027	.072	.100	.080	.026	.100	.214	.092
	2	.030	.079	.078	.048	.029	.103	.203	.073
	3	.024	.077	.077	.052	.025	.103	.219	.073
65	2	.013	.017	.031	.127	.021	.054	.136	.355
	3	.042	.037	.065	.129	.041	.098	.198	.251
67	1	.049	.099	.184	.195	.001	.003	.015	.034
	2	.019	.061	.180	.255	.001	.004	.045	.091
	3	.030	.076	.207	.271	.002	.005	.056	.109
72	1	.031	.058	.121	.202	.012	.028	.082	.189
	2	.032	.058	.140	.194	.007	.016	.076	.156
	3	.061	.085	.148	.125	.013	.029	.060	.089
74	2	.085	.133	.158	.038	.023	.043	.022	.002
	3	.095	.157	.188	.047	.015	.029	.019	.004

Table A.5. Weights for water situations for 2000

Producing area	Land class	Saturated thickness: 0-100 feet depth to water (feet)				Saturated thickness: 100+ feet depth to water (feet)			
		0-50	50-100	100-200	200+	0-50	50-100	100-200	200+
55	1	.036	.036	.124	.044	.076	.076	.271	.154
	2	.041	.041	.132	.059	.089	.089	.265	.145
	3	.038	.038	.109	.051	.099	.099	.250	.132
58	1	.041	.041	.180	.133	.012	.012	.123	.099
	2	.045	.045	.173	.118	.019	.019	.123	.107
	3	.042	.042	.151	.108	.021	.021	.123	.148
63	1	.024	.068	.091	.097	.022	.090	.197	.109
	2	.027	.077	.076	.060	.025	.095	.190	.087
	3	.022	.074	.073	.063	.021	.095	.206	.086
65	2	.012	.017	.031	.160	.018	.046	.115	.341
	3	.041	.036	.063	.153	.037	.089	.179	.249
67	1	.042	.085	.158	.231	.000	.001	.005	.020
	2	.017	.051	.154	.289	.000	.002	.027	.078
	3	.027	.066	.181	.306	.001	.003	.035	.097
72	1	.027	.054	.109	.263	.005	.017	.039	.142
	2	.029	.054	.121	.255	.004	.010	.035	.122
	3	.057	.083	.141	.162	.006	.018	.034	.075
74	2	.074	.126	.154	.048	.020	.037	.021	.003
	3	.081	.146	.182	.061	.010	.022	.017	.005

8. APPENDIX B: WATER LAW

Water law governing irrigation in America is a state responsibility with federal interest limited to negotiating treaties and compacts and navigation. Consequently, a number of different doctrines have developed, and each state has its individual pecularities in application. The formulation of property rights for water is difficult for a number of reasons; water is a fugitive resource, variable in supply, and admits reuse. The value of water depends upon location, quality, and timing of availability, but all may be altered by use, and transportation and storage costs are high relative to value. The different water doctrines have attempted to cope with these factors influenced by the relative importance of different local problems and different histories. In general, the law governing groundwater and surface water is different in most states, but both surface and groundwater can generally be fit into five main doctrines.

The riparian doctrine developed out of English common law and is applicable mainly in the more humid eastern states where plentiful supplies of water are available and in parts of the western states where the common law rule was applied before a more suitable doctrine was articulated. The riparian doctrine makes water rights appurtenant to ownership of riparian land. The owner is not entitled to diminish supplies except for "reasonable use," primarily for domestic purposes.

Another similar doctrine holds that the landowner has absolute rights in the water that is appurtenant to his land. He can use, misuse, sell, or otherwise dispose of such water without regard to the effect upon his neighbors except for restrictions upon malicious conduct. This doctrine originally applied to diffuse surface waters, a fairly insignificant water source, but is important because it has frequently been extended to groundwater which is nearly all diffuse. Externalities are also more common with diffuse groundwater, as aquifers may be very large (like the Ogallala) rather than a local phenomena as diffuse surface water.

A third doctrine is prior appropriation which has developed in the arid west. This doctrine holds that water rights specified in terms of time, place, use, and rate of diversion are vested in priority according to priority in time of those who have diverted water. The water right is severed from the land and ownership of the land where the water is diverted. Owners of junior water rights, defined according to the earliest date of diversion, are allowed to exercise their rights only if there is sufficient water to supply all senior appropriators. The water has to be applied to a "beneficial" use analogous to the "reasonable" use criteria of the riparian doctrine.

The correlative rights doctrine is a more recent development in America. Under the correlative rights doctrine, all property owners have a proportional right in water available. Limited supplies are allocated to each individual according to his portion of the total available. The individual's portion is determined by his share in the total land to which the water is appurtenant. This doctrine is presently applied to surface water in parts of California and groundwater in some other states.

Another recent development is the permit doctrine first adopted in Iowa in 1956. Under the permit system, water is declared to be the property of the state to be administered in the public interest. The state then issues a temporary right or permit at a nominal fee to make use of the water under specified conditions. The permits are renewable but allow a central authority to reallocate water in response to changing needs.

The doctrines of six states, Nebraska, Colorado, Kansas, Oklahoma, New Mexico, and Texas, are examined below in more detail. The primary purpose is to show the regulation of water withdrawals from the Ogallala Aquifer. But surface water doctrines are discussed first, both because these states more specifically illustrate by example the applications of the doctrines typical of the entire area where irrigation is represented in the model and because groundwater law has tended to follow and adapt to previously formulated surface water law historically.

8.1. Surface Water Law in the Ogallala Zone

The regulation of surface water in all six states overlying the Ogallala Zone is governed by the appropriation doctrine, but Nebraska, Oklahoma, Texas, and Kansas also recognize riparian rights that predate the adoption of the appropriation system. Acquisition of a new right requires a permit[1] in Nebraska, Kansas, Oklahoma, and New Mexico.

[1]This is not the permit doctrine, because the right when acquired is recognized as the property of the permit holder and not the state.

Texas no longer grants appropriation rights for surface water, since it has been determined that all of the state's surface water has been appropriated. Colorado does not require a permit. Each state differs in the exact details for perfecting an appropriation, limitations on transfer of rights and changes in use, and how the rights may be lost.

In general, a right is perfected by putting water to a beneficial use. The right is characterized by the amount of water used, the date it was first used, the place of diversion and return flows, and the use. In times of shortage, rights senior in terms of first use are filled first even though more junior rights are consequently completely unfilled. Preference by use favors domestic uses when cotemporous uses are in conflict. However, in Texas, a proportionate system has been adopted so that all suffer in times of shortage. A weighted system of priorities determines water allocations among the holders of such rights making the system similar to the correlative doctrine except in how the rights are determined. Also irrigators in Nebraska are limited to three acre feet per acre per year.

Transfer of rights is made complicated by the nature of water. More specifically, changes in use in point in time, place of diversion and place, and quantity and quality of return flows may affect other users with equally valid rights which have to be protected. Different states have dealt with this problem in different ways. In Nebraska, irrigation rights are appurtenant to the land on which irrigation takes place. In Oklahoma, a right may be transferred to other land only if it becomes infeasible to use the water on the original land. But except for these two qualifications, appropriation rights are regarded as a real property right and may be severed from land and conveyed. The purpose of use and point of diversion can be changed by applying to the agency which administers water rights and will be approved providing the change does not impair existing rights. Where such a change involves adverse effects on other users, the transfer may still be accomplished but with loss of seniority.

Municipalities and other non-agricultural users may purchase water rights from irrigators subject to approval of state regulatory agencies as described above. Municipalities may also acquire water rights from agricultural users through exercise of eminent domain. In Texas, municipalities may condemn without compensation, but the basis for compensation is not well specified in the other six states.

Finally, water rights may be lost through a continuous period of non-use or abandonment. The length of the period of non-use sufficient for loss of the right varies from three to 18 years in Colorado.

8.2. Groundwater Law in the Ogallala Zone

According to Dewsnup and Jenson (1973), early formulations of groundwater law were based upon misconceptions concerning the physical characteristics of groundwater. It was assumed that groundwater and surface water were independent, and, consequently, withdrawals of groundwater would not affect surface water flows. It was also assumed that underground streams in definite channels were common which could therefore be administered as surface water.[1] This last assumption

[1] This assumption is also related to a need to locate the streams before constructing a well and the practice of dowsing and water witches.

has subsequently been reversed so the presumption is now generally made that underground water is diffuse; it percolates, seeps, filters, and moves through the soil as is indeed the case for the large majority of groundwater.

Because of these assumptions, many states treated groundwater as the property of the landowner where it occurred, applying the doctrine of absolute rights used for diffuse surface waters. The landowner could make use of or sell as much groundwater as he could capture without regard to concern for reasonable or beneficial use or damage to the water rights of other landowners. This system regulated groundwater use in New Mexico until 1931, Kansas until 1945, Oklahoma until 1949, Colorado until 1957, and is still in force in Texas. In contrast, groundwater has always been subject to appropriation in Nebraska. In Nebraska, the appropriation was subject to reasonable use qualifications and the courts recognized correlative rights for times of shortage.

The six states have adopted different means to provide a more equitable means of recognizing groundwater rights. Oklahoma, Colorado, and New Mexico have established a procedure by which a state agent issues permits to appropriate groundwater in designated groundwater basins. The agent is the State Engineer in New Mexico, the Water Resources Board in Oklahoma, and the Groundwater Commission in Colorado. The procedures for designating such basins and conditions by which a permit is allowed or disallowed is established by statute. The Oklahoma statute sets an upper limit to total withdrawals from a basin equal to annual recharge, thus proscribing mining. Courts in both Colorado and New Mexico have supported regulatory decisions disallowing new appropriations so that the rate of groundwater mining taking place in an area would not be too rapid implicitly recognizing controlled mining.

Kansas declared groundwater subject to state regulation and appropriation in 1945. Such appropriations are enjoined only if an "unreasonable" lowering of the water table which adversely affects existing owners results. Nebraska has always used the reasonable use doctrine as a guide to appropriating groundwater. Since 1957, Nebraska has enforced a centralized permit system whereby new irrigation wells must be at least 600 feet from all pre-existing irrigation wells on adjoining property.

The three states, Nebraska, Kansas, and Texas, have also enacted legislation for the voluntary formation of groundwater conservation districts. The only effective control on groundwater mining in these states is by rules formulated by these districts. Two such districts had been formed by 1972 in Nebraska. At that time, Nebraska changed its policy and divided the state into natural resource districts. Groundwater "control areas" can now be formed at the initiation of the natural resource districts. The districts can establish rules regulating runoff, well spacing, tax (limited to ¼ of one mill for administrative costs only), and even limit total withdrawals.

By 1979, five groundwater management districts had been formed in Kansas. The districts' substantive powers are to levy a tax of 60¢ per acre foot and 5¢ per acre foot or less (again, for administrative costs), regulate well spacing and return flows, and to recommend the formation of an "intensive groundwater use control area" where mining exists. The Chief Engineer of the state may close such an area to further appropriations and determine permissible total withdrawals to be apportioned among users according to priority of rights, but such controls have not been exercised so far.

Similar districts can be formed in Texas. The Texas districts have the power to regulate well spacing and formulate and enforce rules to prevent wasteful uses. The districts are the only form of control in Texas; the water remains the property of landowners, and there has been no suggestion of directly limiting total withdrawals.

The districts appear to have substantive powers to limit withdrawals from the Ogallala Aquifer in certain areas. In practice, however, the districts have not exercised these powers. The only rules formulated by districts in Kansas and Texas have been either administrative or dealing with well spacing and tail-water. Spacing requirements limit well interference but do not really limit withdrawals. Taxes levied are by statute at a level to provide administrative expenses rather than restrain withdrawals.

There is an exception. Restrictive regulations have been formulated for a designated control area covering parts of Chase, Perkins, and Dundy counties in the Upper Republican Natural Resource District of Nebraska. The regulations require the installation of flow meters on irrigation wells and limit withdrawals to an anticipated average of 14 to 17 inches per acre per year over five-year periods. The objective is to limit declines in the water table to one percent of the saturated thickness of the aquifer per year. If successful, this district may provide a model for limiting groundwater withdrawals for the rest of Nebraska and Kansas. But a major change in groundwater law would be necessary before this approach could be used in that state. It seems likely that local support for the regulation will weaken if the externalities from irrigation in adjoining regions vitiate the beneficial effect of the regulation, as seems likely to be the case until much larger control districts are established.

9. APPENDIX C: ENERGY COEFFICIENTS USED IN THE MODEL

Energy coefficients for crop production including energy for machine operation energy by crop, tillage practice, and PA, energy for crop drying, and energy used in the manufacture of nitrogen and other fertilizers and pesticides are taken from Dvoskin, Heady, and English (1978). Diesel required for crop transportation also is taken from that source. Energy coefficients for irrigation are estimated as described below.

The fuel conversion efficiencies shown in Table C.1 are assumed by type of engine. These efficiencies give the amount of energy converted to useful work by the various types of irrigation engines from which it is possible to calculate the fuel needed to lift one acre foot of

Table C.1. Fuel conversion efficiencies assumed for irrigation motors

Fuel	Units	Units per horsepower hour[a]	Units to lift 1 acre foot 1 foot	Efficiency (percent)
Diesel	gallon	0.0728	0.0998	25
Liquid petroleum gas	gallon	0.1220	0.1673	22
Natural gas	1,000 cubic feet	0.0110	0.151	22
Electricity	kilowatt hour	0.848	1.1630	88

[a]Source: Kletke _et al._ (1978).

water one foot, as given in Table C.1, assuming a perfectly efficient pump and the energy value of diesel, liquid petroleum gas, natural gas, and electricity is 140.0, 94.5, 1.0675, and 3.41 MBTU's, respectively. However, a perfectly efficient pump is not realistic; it is assumed that pump overall system efficiency is reduced to 58.2 above energy losses due to engine efficiency primarily because of pump efficiency.

The distance the water needs to be lifted is from the surface of the well to ground level, or the pumping lift. These values are taken from Dvoskin and Heady (1976). In addition, additional energy is needed to create pressure and overcome friction in moving the water through pipes and, in the case of water distributed by gravity, to provide the gravitational potential energy needed. The energy required can all be conveniently expressed as potential energy or head that the water would have to have to provide the pressure and overcome friction. The head assumed by distribution system is given in Table C.2. The total dynamic head is defined as the sum of the pumping lift and head needed for pressure and friction, and represents the change in potential energy required to apply the water expressed in terms of distance the water need be raised in feet.

Table C.2. Head required for pressure and friction to deliver water in the field

System	Head
	(feet)
Sprinklers	
Center pivot	180
Hand move, towline, side role	160
Big gun, traveling gun[a]	312
Solid set[a]	175
Drip or trickle[a]	115
Surface	
Open ditch, flood, syphon tubes	5
Gated pipe	45

[a]Source: Dvoskin and Heady (1976).

The distributions of various systems in the same PA determine the average head needed to overcome pressure and friction within a PA. The proportions for the most important systems are given in Table C.3. The average head by system by PA is given in Table C.4. Also given in Table C.4 is the total dynamic head for groundwater and surface water where the average pumping lift for both ground and surface water has been added to the system head.

The amount of fuel required per acre foot of water applied by PA is the total dynamic head (Table C.4) times the fuel coefficient from Table C.1 divided by the pumping unit efficiency of 58.2. The average amount of each fuel for each acre foot needs to take account of the proportion of each type of fuel used in each PA. The proportions used are given in Table C.5, which are derived from state data given in the Irrigation Journal (1978) weighted to PA. Mathematically, the method can be expressed as

$$F_{ij} = T_{ij}\, C_i\, W_i \,/\, 0.582 \qquad \text{(C.1)}$$

$i = 1, 2, 3, 4$ for the fuel types,

$j = 1, 2$ for surface and groundwater,

where

F is the amount of fuel required,

T is the total dynamic head from Table C.4,

C is the coefficient from Table C.2, and

W is the fuel weight from Table C.5.

Gasoline is converted into diesel in presenting final results in Tables C.6 and C.7.

Table C.3. Distribution of the irrigation systems by PA[a]

PA	Surface	Center pivot	Other sprinkler
48	.901	.070	.029
49	.592	.095	.312
50	.908	.034	.058
51	.906	.053	.040
52	.570	.288	.142
53	.169	.527	.305
54	.787	.161	.052
55	.637	.243	.120
56	.335	.439	.226
57	.449	.339	.212
58	.642	.279	.079
59	.767	.107	.126
60	.200	.609	.191
61	.693	.183	.124
62	.864	.048	.088
63	.691	.252	.057
64	.312	.305	.383
65	.824	.135	.040
66	.175	.497	.328
67	.960	.020	.020
68	.534	.080	.385
69	.336	.194	.469
70	.852	.016	.132
71	.733	.093	.174
72	.861	.058	.081
73	.428	.085	.487
74	.136	.284	.580
75	.518	.135	.347
76	.443	.132	.425
77	.723	.256	.021
78	.916	.028	.057
79	.925	.015	.059
80	.933	.035	.032
81	.954	.014	.032
82	.886	.020	.095
83	.960	.008	.032
84	.823	.019	.158
85	.843	.011	.146
86	.854	.054	.092
87	.960	.023	.017
88	.577	.040	.382

[a]Source: Department of Commerce (1977).

Table C.3. Continued

PA	Surface	Center pivot	Other sprinkler
89	.779	.028	.192
90	.660	.032	.307
91	.922	.016	.062
92	.368	.054	.578
93	.375	.150	.474
94	.547	.082	.371
95	.424	.095	.481
96	.090	.076	.834
97	.090	.076	.834
98	.477	.107	.416
99	.223	.086	.690
100	.655	.036	.309
101	.792	.021	.186
102	.547	.066	.386
103	.456	.049	.496
104	.691	.050	.260
105	.694	.003	.302

Table C.4. Total dynamic head estimated by PA

PA	System	Total dynamic head: Groundwater	Total dynamic head: Surface water
48	23.59	68.67	32.41
49	71.31	200.35	80.14
50	21.73	63.81	30.55
51	22.56	137.56	28.28
52	91.30	251.25	151.53
53	153.25	176.12	216.47
54	57.40	153.42	60.34
55	87.29	158.37	93.14
56	128.24	171.40	134.09
57	119.78	164.64	129.03
58	84.75	277.39	88.27
59	68.96	233.39	74.75
60	154.96	196.49	160.56
61	72.80	155.20	77.81
62	44.39	121.64	46.06
63	83.84	279.43	87.77
64	131.03	195.85	136.54
65	53.64	389.91	61.54
66	149.01	309.86	157.49
67	31.10	251.07	40.00
68	96.66	247.87	105.17
69	123.46	270.10	128.51
70	47.13	113.06	56.04
71	65.22	163.81	74.12
72	39.08	279.68	44.45
73	110.46	249.44	119.36
74	154.75	291.25	163.46
75	97.49	249.81	106.40
76	108.60	283.86	117.50
77	67.40	121.73	69.07
78	21.03	378.31	22.22
79	36.21	224.20	45.11
80	17.72	230.16	18.46
81	31.94	79.82	40.84
82	27.97	169.94	30.10
83	30.43	225.65	32.14
84	43.31	361.01	44.71
85	30.72	215.91	30.72
86	31.17	261.87	31.42
87	13.36	395.17	13.37
88	79.07	331.65	80.23
89	55.58	282.72	57.53
90	62.95	277.07	63.36

Table C.4. Continued

PA	System	Total dynamic head Groundwater	Surface water
91	21.14	357.10	21.55
92	105.16	218.95	120.62
93	110.20	370.81	217.63
94	78.42	354.97	79.32
95	99.41	342.28	154.16
96	154.05	263.14	219.02
97	149.91	338.24	274.04
98	91.65	182.56	154.97
99	132.20	263.73	157.10
100	71.54	120.02	71.72
101	52.56	187.90	52.74
102	86.82	143.15	87.00
103	98.93	203.33	99.11
104	66.99	199.02	67.17
105	65.60	182.82	65.78

Table C.5. Proportions of fuel types used in irrigation by PA[a]

PA	Gasoline	Natural gas	Liquid petroleum gas	Electricity	Diesel
48	.042	.001	.010	.114	.833
49	.042	.001	.010	.114	.833
50	.042	.001	.010	.114	.833
51	.025	.021	.015	.096	.842
52	.043	.018	.120	.186	.634
53	.042	.084	.170	.265	.440
54	.021	.102	.093	.106	.679
55	.010	.230	.140	.350	.270
56	.010	.230	.140	.350	.270
57	.144	.124	.115	.318	.299
58	.015	.340	.120	.186	.339
59	.010	.236	.139	.346	.268
60	.198	.137	.304	.167	.194
61	.250	.037	.387	.125	.200
62	.030	.100	.120	.050	.700
63	.012	.572	.102	.116	.198
64	.186	.164	.325	.115	.210
65	.014	.544	.088	.064	.292
66	.028	.487	.135	.078	.272
67	.000	.600	.050	.050	.300
68	.022	.511	.117	.072	.278
69	.092	.379	.161	.123	.245
70	.001	.597	.050	.053	.299
71	.000	.600	.050	.050	.300
72	.004	.585	.058	.054	.300
73	.000	.600	.050	.050	.300
74	.004	.583	.059	.054	.300
75	.000	.600	.050	.050	.300
76	.000	.600	.050	.050	.300
77	.030	.100	.120	.050	.700
78	.034	.463	.118	.084	.300
79	.000	.600	.050	.050	.300
80	.050	.400	.150	.100	.300
81	.000	.600	.050	.050	.300
82	.020	.038	.038	.069	.835
83	.030	.100	.120	.050	.701
84	.033	.109	.103	.057	.698
85	.006	.313	.019	.013	.649
86	.002	.265	.002	.016	.714
87	.001	.303	.004	.003	.688

[a]Source: Irrigation Journal (1978).

Table C.5. Continued

PA	Gasoline	Natural gas	Liquid petroleum gas	Electricity	Diesel
88	.029	.002	.023	.048	.897
89	.034	.000	.027	.059	.880
90	.010	.000	.010	.200	.780
91	.010	.000	.010	.200	.780
92	.038	.001	.009	.104	.847
93	.000	.000	.000	.008	.992
94	.009	.009	.009	.010	.964
95	.006	.006	.006	.007	.976
96	.000	.000	.000	.001	.999
97	.000	.000	.000	.010	.990
98	.000	.000	.000	.000	1.000
99	.000	.009	.000	.000	.991
100	.000	.020	.000	.000	.980
101	.000	.020	.000	.000	.980
102	.000	.020	.000	.000	.980
103	.000	.020	.000	.000	.980
104	.000	.020	.000	.000	.980
105	.000	.020	.000	.000	.980

Table C.6. Fuel needed to apply one acre foot of groundwater by PA

PA	Diesel	Natural gas	Liquid petroleum gas	Electricity
	(gallons)	(1,000 cubic feet)	(gallons)	(kilowatt hours)
48	1.97	0.002	0.20	114.3
49	5.76	0.005	0.58	333.5
50	1.83	0.001	0.18	106.2
51	3.02	0.075	0.59	231.5
52	10.38	0.117	8.67	318.3
53	9.62	0.383	8.61	154.9
54	3.49	0.406	4.10	208.2
55	9.86	0.944	6.37	85.4
56	10.67	1.022	6.90	92.5
57	14.17	0.529	5.44	98.4
58	9.76	2.445	9.57	187.9
59	14.36	1.428	9.32	125.0
60	14.14	0.698	17.17	76.2
61	11.81	0.149	17.27	62.0
62	1.84	0.315	4.20	170.1
63	6.29	4.143	8.19	110.6
64	11.83	0.833	18.30	82.2
65	5.47	5.498	9.86	227.5
66	6.04	3.911	12.03	168.4
67	2.15	3.905	3.61	150.5
68	4.25	3.283	8.34	137.7
69	11.13	2.653	12.50	132.2
70	1.05	1.750	1.63	67.6
71	1.41	2.548	2.35	98.2
72	2.84	4.241	4.66	167.7
73	2.13	3.879	3.59	149.5
74	2.95	4.401	4.94	174.6
75	2.14	3.885	3.59	149.8
76	2.43	4.415	4.08	170.2
77	1.84	0.316	4.20	170.3
78	8.26	4.540	12.83	226.8
79	1.92	3.487	3.22	134.4
80	6.47	2.386	9.92	138.0
81	0.68	1.241	1.15	47.8
82	2.75	0.167	1.86	283.6
83	3.41	0.585	7.78	316.1
84	6.14	1.020	10.69	503.5
85	0.76	1.752	1.18	280.0
86	0.83	1.799	0.15	373.6
87	0.29	3.104	0.45	543.3

Table C.6. Continued

PA	Diesel	Natural gas	Liquid petroleum gas	Electricity
	(gallons)	(1,000 cubic feet)	(gallons)	(kilowatt hours)
88	4.83	0.017	2.19	594.5
89	4.96	0.000	2.19	497.2
90	10.11	0.000	0.79	431.9
91	13.03	0.000	1.03	556.6
92	5.73	0.006	0.57	370.6
93	0.57	0.000	0.00	735.1
94	1.31	0.083	0.92	683.8
95	0.86	0.053	0.59	667.6
96	0.05	0.000	0.00	525.3
97	0.58	0.000	0.00	669.1
98	0.00	0.000	0.00	364.8
99	0.00	0.062	0.00	522.3
100	0.00	0.062	0.00	235.0
101	0.00	0.097	0.00	368.0
102	0.00	0.074	0.00	280.3
103	0.00	0.105	0.00	398.2
104	0.00	0.103	0.00	389.7
105	0.00	0.095	0.00	358.0

Table C.7. Fuel needed to apply one acre foot of surface water by PA

PA	Diesel	Natural gas	Liquid petroleum gas	Electricity
	(gallons)	(1,000 cubic feet)	(gallons)	(kilowatt hours)
48	0.93	0.001	0.09	54.0
49	2.30	0.002	0.23	134.0
50	0.88	0.001	0.09	50.9
51	0.62	0.015	0.12	47.6
52	6.26	0.071	5.23	192.0
53	11.83	0.471	10.58	190.3
54	1.37	0.160	1.61	81.9
55	5.80	0.555	3.75	50.3
56	8.34	0.799	5.40	72.3
57	11.10	0.415	4.27	77.1
58	3.11	0.778	3.05	59.8
59	4.60	0.457	2.99	40.0
60	11.55	0.570	14.03	62.2
61	5.92	0.075	8.66	31.1
62	0.70	0.119	1.59	64.4
63	1.98	1.301	2.57	34.7
64	8.25	0.580	12.76	57.3
65	0.86	0.868	1.56	35.9
66	3.07	1.988	6.11	85.6
67	0.34	0.622	0.58	24.0
68	1.81	1.393	3.54	58.4
69	5.30	1.262	5.95	62.9
70	0.52	0.867	0.81	33.5
71	0.64	1.153	1.07	44.4
72	0.45	0.674	0.74	26.6
73	1.02	1.856	1.72	71.6
74	1.66	2.470	2.77	98.0
75	0.91	1.655	1.53	63.8
76	1.01	1.827	1.69	70.4
77	1.05	0.179	2.38	96.6
78	0.49	0.267	0.75	13.3
79	0.39	0.702	0.65	27.0
80	0.52	0.191	0.80	11.1
81	0.35	0.635	0.59	24.5
82	0.49	0.030	0.33	50.2
83	0.49	0.083	1.11	45.0
84	0.76	0.126	1.32	62.4
85	0.11	0.249	0.17	39.8
86	0.10	0.216	0.02	44.8
87	0.01	0.105	0.02	18.4

Table C.7. Continued

PA	Diesel	Natural gas	Liquid petroleum gas	Electricity
	(gallons)	(1,000 cubic feet)	(gallons)	(kilowatt hours)
88	1.17	0.004	0.53	143.8
89	1.01	0.000	0.45	101.2
90	2.31	0.000	0.18	98.8
91	0.79	0.000	0.06	33.6
92	3.15	0.003	0.31	204.2
93	0.30	0.000	0.00	431.4
94	0.29	0.019	0.21	152.8
95	0.39	0.024	0.27	300.7
96	0.04	0.000	0.00	437.2
97	0.47	0.000	0.00	542.1
98	0.00	0.000	0.00	309.7
99	0.00	0.037	0.00	311.1
100	0.00	0.037	0.00	140.5
101	0.00	0.027	0.00	103.3
102	0.00	0.045	0.00	170.9
103	0.00	0.051	0.00	194.1
104	0.00	0.034	0.00	131.5
105	0.00	0.034	0.00	128.8

Energy coefficients for withdrawals from the Ogallala Aquifer vary, of course, with the water situation. The coefficients used are given in Table C.8 and Table C.9. The coefficients in Table C.9 are for center pivot system rather than a weighted average of the systems. These coefficients were used on land class 3, because this land class has a steeper slope, making center pivots necessary.

Table C.10 shows the energy prices used in the model. The energy prices are estimated by market region for diesel, natural gas, LPG, and electricity. Diesel prices by state for 1975 were taken from the Department of Agriculture (1975); electricity and LPG prices by state for 1975 were taken from the Department of Energy;[1] 1975 deregulated[2] natural gas prices by market region are given in Dvoskin, Heady, and English (1978). Diesel and LPG prices are adjusted by state for taxes given by the Department of Transportation (1976). Diesel, LPG, and electricity prices are then weighed from states to market regions and increased by 114, 156, and 104 percent, respectively, to make them double average energy prices for the period 1975-79.[3] The resultant prices, as given in Table C.10, were used in Solutions I and III 1990 and Solution I 2000. These prices were doubled again for Solution II 1990 and Solution II 2000.

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[1]Personal communication.

[2]The prices of natural gas in 1975 as if the industry were deregulated.

[3]See discussion on pages 14 and 15 and Table 1.3.

Table C.8. Irrigation coefficients for water from the Ogallala Aquifer

Producing area	Water situation	Diesel	Natural gas	LPG[a]	Electricity
			(units per acre foot[b])		
55	1	10.15	0.98	6.61	88.63
	2	13.23	1.28	8.62	115.61
	3	17.86	1.72	11.64	156.07
	4	24.04	2.32	15.67	210.02
	5	11.33	1.09	7.39	99.02
	6	14.42	1.39	9.40	125.99
	7	19.05	1.84	12.42	166.46
	8	25.23	2.44	16.44	220.41
58	1	5.05	1.29	5.05	99.20
	2	6.77	1.73	6.78	133.07
	3	9.36	2.39	9.36	183.87
	4	12.81	3.27	12.81	251.61
	5	5.68	1.45	5.68	111.58
	6	7.40	1.89	7.41	145.45
	7	9.99	2.55	9.99	196.25
	8	13.44	3.43	13.44	263.99
63	1	3.63	2.45	4.84	68.36
	2	4.66	3.15	6.22	83.96
	3	6.34	4.27	8.46	114.03
	4	8.50	5.73	11.33	152.93
	5	3.97	2.68	5.30	71.52
	6	5.07	3.42	6.77	91.30
	7	6.71	4.53	8.97	120.97
	8	8.91	6.02	11.90	160.54
65	1	1.88	1.98	3.55	81.36
	2	2.55	2.68	4.82	110.33
	3	3.55	3.74	6.71	153.79
	4	4.89	5.15	9.24	211.74
	5	1.81	1.91	3.43	78.46
	6	2.48	2.61	4.69	107.43
	7	3.48	3.67	6.59	150.90
	8	4.82	5.08	9.12	208.84

[a]Liquid petroleum gas.

[b]The units are gallons for diesel and LPG, 1,000 cubic feet for natural gas, and kilowatt hours for electricity.

Table C.8. Continued

Producing area	Water situation	Diesel	Natural gas	LPG	Electricity
			(units per acre foot)		
67	1	0.00	1.79	2.10	94.50
	2	0.00	2.51	2.94	132.80
	3	0.00	3.59	4.22	190.20
	4	0.00	5.04	5.91	266.70
	5	0.00	1.71	2.01	90.70
	6	0.00	2.44	2.86	128.97
	7	0.00	3.52	4.13	186.37
	8	0.00	4.97	5.83	262.90
72	1	0.03	2.98	1.10	93.96
	2	0.04	3.88	1.43	122.24
	3	0.05	5.23	1.93	164.65
	4	0.07	7.02	2.59	221.20
	5	0.02	2.81	1.03	88.31
	6	0.04	3.70	1.36	116.58
	7	0.05	5.05	1.86	159.00
	8	0.07	6.85	2.52	215.55
74	1	2.39	3.63	4.07	143.85
	2	2.89	4.38	4.92	173.82
	3	3.63	5.52	6.19	218.78
	4	4.63	7.02	7.87	278.73
	5	2.29	3.48	3.90	137.85
	6	2.79	4.23	4.75	167.83
	7	3.53	5.36	6.02	212.79
	8	4.53	6.88	7.72	272.74

Table C.9. Irrigation coefficients for water from the Ogallala Aquifer for land class three

Producing area	Water situation	Diesel	Natural gas	LPG[a]	Electricity
			(units per acre foot[b])		
55	1	15.86	1.53	10.34	138.54
	2	18.95	1.83	12.35	165.52
	3	23.57	2.28	15.37	205.98
	4	29.75	2.87	19.39	259.94
	5	17.37	1.68	11.32	151.76
	6	20.46	1.98	13.33	178.74
	7	25.09	2.42	16.35	219.20
	8	31.27	3.02	20.38	273.16
58	1	8.85	2.26	8.86	173.95
	2	10.58	2.70	10.58	207.82
	3	13.16	3.36	13.17	258.62
	4	16.61	4.25	16.62	326.36
	5	9.70	2.48	9.70	190.55
	6	11.42	2.92	11.43	224.42
	7	14.01	3.58	14.01	275.22
	8	17.46	4.46	17.47	342.96
63	1	6.16	4.16	8.23	111.01
	2	7.11	4.80	9.50	128.06
	3	8.81	5.95	11.77	158.71
	4	10.91	7.37	14.58	196.63
	5	6.53	4.41	8.72	117.62
	6	7.63	5.15	10.18	137.40
	7	9.27	6.26	12.38	167.08
	8	11.47	7.74	15.32	206.65
65	1	3.42	3.60	6.46	147.96
	2	4.09	4.31	7.72	176.94
	3	5.09	5.36	9.62	220.40
	4	6.43	6.77	12.15	278.35
	5	3.35	3.53	6.33	145.07
	6	4.02	4.24	7.60	174.04
	7	5.02	5.29	9.50	217.50
	8	6.36	6.70	12.02	275.45

[a]Liquid petroleum gas.

[b]The units are gallons for diesel and LPG, 1,000 cubic feet for natural gas, and kilowatt hours for electricity.

Table C.9. Continued

Producing area	Water situation	Diesel	Natural gas	LPG	Electricity
		(units per acre foot)			
67	1	0.00	3.69	4.33	195.41
	2	0.00	4.42	5.18	233.68
	3	0.00	5.50	6.45	291.08
	4	0.00	6.95	8.15	367.61
	5	0.00	3.62	4.25	191.59
	6	0.00	4.34	5.09	229.85
	7	0.00	5.43	6.37	287.25
	8	0.00	6.88	8.06	363.79
72	1	0.04	4.42	1.63	139.12
	2	0.05	5.32	1.96	167.40
	3	0.06	6.66	2.45	209.81
	4	0.08	8.46	3.11	266.36
	5	0.04	4.24	1.56	133.47
	6	0.05	5.14	1.89	161.68
	7	0.06	6.49	2.39	204.16
	8	0.08	8.28	3.05	260.71
74	1	2.45	3.72	4.17	147.48
	2	2.95	4.47	5.02	177.46
	3	3.69	5.61	6.29	222.42
	4	4.69	7.12	7.99	282.36
	5	2.35	3.57	4.00	141.49
	6	2.85	4.32	4.85	171.46
	7	3.59	5.46	6.12	216.42
	8	4.59	6.97	7.82	276.37

Table C.10. Energy prices used in the model[a]

Market region	Diesel	Natural gas	LPG[b]	Electricity
		(dollars per unit[c])		
1	0.610	8.24	0.692	0.0857
2	0.563	8.13	0.641	0.0953
3	0.567	8.65	0.567	0.0721
4	0.648	8.73	0.568	0.0562
5	0.630	6.59	0.557	0.0686
6	0.605	8.46	0.572	0.0822
7	0.599	7.21	0.562	0.0692
8	0.554	7.38	0.539	0.0701
9	0.566	6.56	0.540	0.0524
10	0.550	5.94	0.536	0.0565
11	0.528	5.48	0.552	0.0531
12	0.561	7.03	0.539	0.0659
13	0.592	6.59	0.539	0.0668
14	0.547	6.99	0.533	0.0623
15	0.549	6.71	0.537	0.0686
16	0.552	5.96	0.566	0.0481
17	0.527	6.14	0.538	0.0551
18	0.615	4.97	0.520	0.0503
19	0.534	6.17	0.538	0.0495
20	0.524	6.50	0.539	0.0498
21	0.536	5.71	0.595	0.0489
22	0.541	6.33	0.543	0.0496
23	0.544	6.11	0.583	0.0510
24	0.543	9.38	0.600	0.0312
25	0.639	5.75	0.609	0.0464
26	0.590	7.28	0.612	0.0643
27	0.717	7.18	0.617	0.0566
28	0.721	7.03	0.619	0.0572

[a]These prices were doubled for Solution II 1990 and Solution II 2000.

[b]Liquid petroleum gas.

[c]The units are gallons for diesel and LPG, 1,000 cubic feet for natural gas, and kilowatt hours for electricity.