A REGIONAL PROBLEM IN A NATIONAL CONTEXT: THE OGALLALA AQUIFER

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The Ogallala 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 aerial extent of the aquifer (Figure 1) includes the eastern tier of counties in Colorado and New Mexico, the western third of Kansas, the greater part of the state of Nebraska, and the Texas and Oklahoma "panhandles." The last four decades have seen extensive development of irrigation in this area primarily using water from the Ogallala Aquifer and from sporadically occurring overlying alluvial aquifers. By 1974, more than 20 percent of the 41 million irrigated acres in the United States were using water from these sources. Because the water withdrawn greatly exceeds recharge, the water table has been falling throughout the area. Development of irrigation greatly aided the rural economy of the region. Consequently, depletion of the water supply can have adverse effects on employment and income in the region.

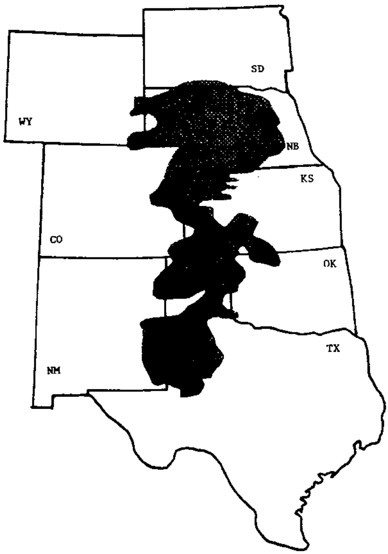

Figure 1. The Ogallala Aquifer Adapted from McGuinnes [5].

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Development of the aquifer took place first in Texas and New Mexico, south of the Canadian River, and it is here where the decline of the water table has been subject of growing concern for many years. The area under irrigation with water from the Ogallala Aquifer appears to have peaked in this area as projected by Hughes and Harman [2]. But continued expansion in the area irrigated from the rest of the aquifer is feasible. Bekure [1] projected the area irrigated in the central portion between the Canadian and Arkansas Rivers to expand at least until the last decade of the present century. Estimates have not yet been made of the scope for expansion north of the Arkansas River but our investigations show that large increases in the area irrigated are feasible.

The likely course of development from the Ogallala Aquifer, however may be determined by events occurring outside the region as well as the falling water table within the region. Rising productivity throughout the United States has historically led to agricultural surpluses and excess productive capacity despite rapidly increasing export demands. In addition, energy prices reversed long-term downward trends in 1973 and are likely to increase rapidly relative to the prices of other agricultural inputs. Crop production with pumped water is particularly energy intensive and, consequently, increased energy prices may accelerate the decline in irrigation from the Ogallala Aquifer.

The work of both Mapp and Dobbins [4] and Young and Coomer [9] demonstrate this possibility for portions of the aquifer studied in isolation. But increased energy prices affect agriculture in the whole nation shifting up supply and commodity prices; specific regions and productive practices may either gain or lose comptitive advantage, although costs are bound to rise for all production altervatives.

In the long run, water withdrawn from the aquifer must decline to recharge levels but the immediate future and the events likely to impact on the immediate future are not obvious. A model recently developed at the Center for Agricultural and Rural Development is described in this paper which may be used to gauge the impacts upon the region of changing demands, energy prices, and the falling water table.

Description of the Model

The model is a regional linear programming model, national in scope with extensive detail on constraints and production possibilities in the area over the Ogallala Aquifer. The model minimizes the cost of satisfying a vector of exogenously determined and fixed demands for ten crops: barley, corn, cotton, legume hay, other hay, oats, sorghum, silage, soybeans, and wheat. Demands are projected for the target year 1990 for the 28 market regions shown in Figure 2 for all crops except cotton. A single national demand is used for cotton. 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 the 105 producing areas shown in Figure 3. 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 projected yields, resources use, and costs that are feasible in a particular producing area. The model determines the prices of all crops as well as all production activities by region.

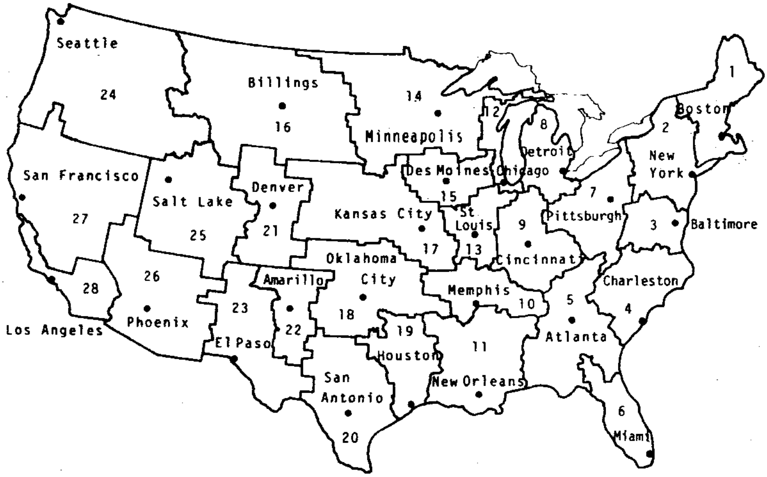

Figure 2. Twenty-eight Market Regions (MR's) of the United States.

Crop production possibilities within producing areas are different for each of the three zones also in Figure 3. Only dryland 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.

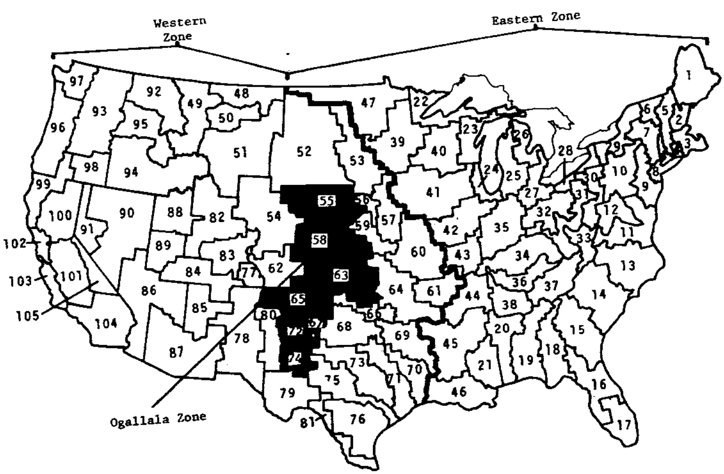

Figure 3. The 105 Producing Areas and the Three Zones.

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. Costs and energy coefficients are modified from relationships found in Kletke, Harris, Mapp [3], assumed well performance characteristics, and historical patterns in the method of application.

The land in the Ogallala Zone is also disaggregated into five land classes according to yield potential and management costs. A discussion of the land classes can be found in Meister and Nicol [6, pp. 42-44]. The eight water situations are used only for land classes one to three, as only a small proportion of irrigated land is in class four and five.

The model is driven by the requirement to satisfy regional demands but is constrained principally by the amount of land available that can be used to satisfy these demands. The model assumes competitive equilibrium and that resources receive their market rate of return except land and water whose returns are determined endogenously. The relationship between land and water determines in large measure how irrigation constraints are formulated.

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 overlie 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 given by Meister and Nicol [6]. The amount of land irrigable with surface water is estimated as the land historically irrigated with surface water from both private and public sources plus furure developments expected to be in use by 1990 for both the Western and Ogallala zones. Surface water available for the endogenous crops is derived from data from the Water Resources Council. [8].

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 for the counties in the shaded areas of the Ogallala Zone shown in Figure 4. 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 areas 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.

Alternatives Examined

The model may be solved under any number of assumptions concerning energy prices and demands. In addition, the model may be solved recursively in that the rates of decline of the water table may be adjusted according to the

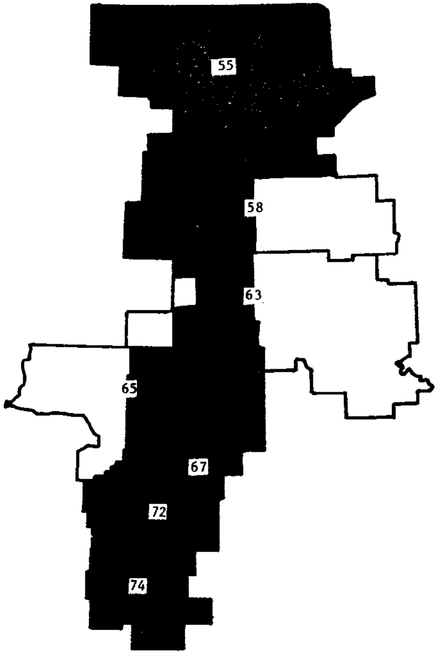

Figure 4. Area Within the Ogallala Zone for Which Water Situation Proportions are Estimated.

water withdrawn to establish new sets of land constraints by water situation for successive solution years for the Ogallala Zone. Three alternatives are described below in the results section of this paper. Each alternative is characterized by a different set of economic conditions assumed to prevail for the year 1990. The alternatives are designed so that the effects of doubled real energy prices and decreased demands are evident from the comparison of model solutions for each alternative.

Alternative I is a base set of assumptions with which other alternatives may be compared to show the effects of these assumptions. Alternative II is identical to Alternative I except that demand levels are reduced by seven percent from Alternative I measured with a Laspeyre quantity index.[1] Energy prices in Alternative II are the same as energy prices in Alternative I. The decreased demand altenative represents a movement along the original supply curve S_1 from a point A to a point B in Figure 5. A comparison of Alternatives I and II illustrate the change in the competitive viability of the region in a framework where demand grows less rapidly than the rates implicit in Alternative I.

[1] The index can be defined as $LI = 100 \sum_{ij} P^{I}_{ij} Q^{II}_{ij} / \sum P^{I}_{ij} Q^{I}_{ij}$ where i=1 to 28 for the market regions; j=1 to 10 for the endogenous crops; LI is the value of the index; P^{I}_{ij} is the price of commodity j in market region i in Alternative I; and Q^{I}_{ij} is the quantity of commodity j, produced in market region i, in Alternative II. etc.

Alternative I and III both incorporate a high export demand scenario and differ only in that energy prices in Alternative II are twice those in Alternative I. The energy prices in Alternative I are double average energy prices in the period 1975-79 and are only moderately higher than current energy prices. The history of energy prices in 1973 and 1979 suggest that the level of energy prices in Alternative III in 1990 are by not means unlikely. A comparison of the results of Alternative III with Alternative I shows the effects of doubled energy prices without any other changes in the model parameters.

The actual effect of doubled energy prices would be to shift the supply function for agricultural commodities upwards. If quantities demanded remain unchanged, all of the adjustment in the market is directed towards increases in the prices of agricultural commodities. A comparison of Alternatives I and III is therefore a comparison of two points like A and C on the vertical demand curve D_1 shown in Figure 5. The actual demand curve would be inelastic but with a negative slope like D_1' in Figure 5 and the actual response to doubled energy prices would be in increase in crop prices and a decrease in quantities demanded. The results for Alternative I should be compared with an alternative corresponding to a point like C′ to accurately reflect the effects of doubled energy prices. But methodological limitations necessitate solving the model with fixed demands. The actual effect of doubled energy prices would be a combination of the results presented for doubled energy prices and reduced demands.

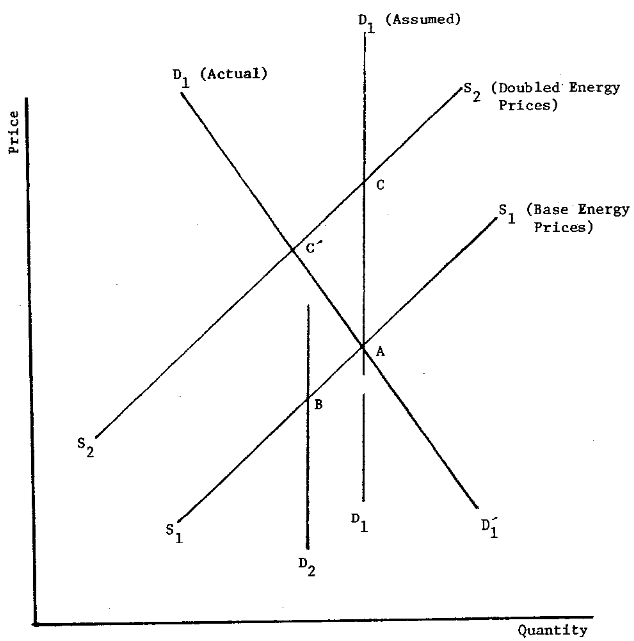

Figure 5. Aggregate Supply and Demand Curves for Agricultural Commodities.

Results

Crop prices in Alternative II are seven to 16 percent less than those in Alternative I depending on crop and market region. As shown in Table 1 the use of all inputs declines with the fall in crop prices and demand but the decline is greatest for inputs associated with irrigation. The largest decline proportionately is in the northern and southern portions of the Ogallala Zones. Crop prices in Alternative III are 27 to 41 percent higher than those in Alternative I. Energy use in Alternative III of course declines but by only 4.1 percent nationwide. A more striking feature of the results for Alternative III is the substitution of other purchased inputs for irrigation. Nearly all the reduction in water applied is associated with converting irrigated land to dryland rather than a reduction in the amount of water applied per acre. The greatest proportionate declines in irrigation for Alternative III are in the northern and southern portions of the Ogallala Zone.

TABLE 1. Regional Changes in Resources Use as a Result of Doubled Energy Prices and Decreased Demands.

ZONE	DOUBLED ENERGY PRICES	DECREASED DEMANDS
	Irrigated Land Use	
Western	-4.5	-23.1
North Ogallala	-55.2	-51.6
Central Ogallala	-14.8	-27.5
South Ogallala	-53.1	-72.0
	Water Use	
Western	-3.9	-26.1
North Ogallala	-56.5	-52.6
Central Ogallala	-13.2	-27.4
South Ogallala	-71.3	-53.6
	Energy Use	
Eastern	0.1	-15.0
Western	-1.2	-16.4
North Ogallala	-25.5	-32.9
Central Ogallala	-1.5	-10.5
South Ogallala	-42.8	-52.2
	Expenditures for Purchased Inputs[a]	
Eastern	8.0	-11.7
Western	11.6	-10.4
North Ogallala	2.8	-19.9
Central Ogallala	10.0	-4.2
South Ogallala	-20.5	-21.9

[a]Includes ownership charges for capital assets but not land.

The fact that risk is ignored may bias all solutions against irrigation but another explanation of the results is equally important. Energy requirements are much greater for irrigated crops in Alternative I: irrigation with groundwater requires an average of 13.3 million British thermal units (MBTUs) per acre compared with 6.4 MBTUs for irrigation with surface water and 2.9 MBTUs for dryland crops. Irrigation has been adopted in a framework of energy prices much lower than the set of low energy prices used in Alternatives I and II. It is only margionally profitable to irrigate a large portion of the area selected for irrigation in Alternative I and irrigation on these lands is at a competitive disadvantage with lower levels of demand or higher energy prices. Furthe more, the effect on irrigation of increased energy prices and decreased demands is complimentary; an increase in energy prices accompanied by a decrease in quantities demanded through the commodity price mechanism would reduce irrigation everywhere and especially irrigation with groundwater in the Ogallala Zone.

The effect of doubled energy prices and decreased demands on economic variables is shown in Table 2. Production is again measured in terms of the Laspeyre quantity index based on Alternative I prices. Decreased demands cause large decreases in production in the southern and northern portions of the Ogallala Zone with smaller declines in the Eastern and Western Zones and the Central portion of the Ogallala Zone.[2] Sales and income from farmland decline by more than production because of the fall in prices. Production

TABLE 2. Regional Effect on Production, Value of Sales, and Income from Farmland of Doubled Energy Prices and Decreased Demands.

ZONE	DOUBLED ENERGY PRICES	DECREASED DEMANDS
	Production	
Eastern	0.9	-7.5
Western	1.6	-5.8
North Ogallala	-13.0	-8.7
Central Ogallala	-2.1	-2.1
South Ogallala	-19.0	-23.8
	Value of Sales	
Eastern	42.2	-21.4
Western	43.3	-20.2
North Ogallala	27.0	-23.2
Central Ogallala	40.6	-16.4
South Ogallala	14.9	-29.2
	Income from Farmland	
Eastern	55.9	-25.8
Western	57.2	-23.8
North Ogallala	47.6	-23.9
Central Ogallala	60.0	-26.7
South Ogallala	59.7	-30.5

[2] Another way of showing the competitive portion of the Ogallala Zone is in the arc elasticity of supply. Arc elasticity of supply is 0.44 nationally (.44 percent decrease in production for one percent fall in prices) but 0.60 in the Ogallala Zone. The arc elasticity is estimated by

$$E = (\sum_{ij} P^{I}_{ij} Q^{II}_{ij} - \sum_{ij} P^{I}_{ij} Q^{I}_{ij})/(\sum_{ij} P^{II}_{ij} Q^{I}_{ij} - \sum_{ij} P^{I}_{ij} Q^{II}_{ij})$$

where E is the arc elastiticy, and i, j, $P^{I}_{ij} Q^{II}_{ij}$ are defined previously for equation (1).

shifts from the Ogallala Zone especially the northern and southern portions to the Eastern and Western Zones with doubled energy prices. Because of the increase in crop prices in Alternative III the value of sales and returns from farmland increases in all zones even the South Ogallala where production is reduced 19 percent.

The reason returns to land increases is that land is a good substitute for energy. When energy prices increase the value of land increases. But the increases in returns to land are not equally distributed even within a zone as shown in Table 3. Land in the entire Ogallala is divided into three categories according to whether it is 1) irrigated in the base (Alternative I) and the alternative compared with the base, 2) irrigated in the base and not irrigated in the alternative compared with the base, and 3) not irrigated in Alternative I. Income increases the most for doubled energy prices (Alternative III) and decreases the least for decreased demands (Alternative II) for land in the third category. Income increases the least for land which is irrigated in both Alternative I and the alternative compared with the base alternative. The land that reverts to dryland because of increased energy prices or decreased demand is the land most marginally profitable to irrigate in Alternative I. Income from this land is very close to income from non-irrigated land because of high production costs due to pumping lifts and other factors. Land in the third category becomes more crucial to satisfy regional demands because of the decrease in production in the area and the returns to land in the third category increases more than the average.

TABLE 3. Changes in Income from Farmland in the Ogallala Zone.

Land Use Category	Increased Energy Prices	Decreased Demand
Continuously irrigated[a]	45.2	-33.3
Switched to dryland[b]	49.5	-30.7
Other land in Ogallala Zone	56.2	-25.0
Total	54.8	-26.1

[a] Irrigated from the Ogallala Aquifer in the base and alternative solution being compared with base.
[b] Converted to dryland in alternate solution.

In summary, the effect of either doubled energy prices or decreased demands is to cause large shifts in production practices especially in the Ogallala Zone. The area irrigated (8.4 million acres in Alternative I) declines 55.1 percent for Alternative II and 43.5 percent for Alternative III and there are substantial reductions in production throughout the region. Farm incomes and purchased inputs decline with decreased demands. But doubled energy prices brings about higher farm incomes (returns to farmland) because the increase in crop prices is greater than the increase in costs while nationally production is maintained with substitution of other purchase inputs for irrigation. The use of purchased inputs increases in the northern and central portions of the Ogallala Zone but declines 20 percent in the South Ogallala Zone. Farmers would benefit from higher incomes including farmers in the Ogallala Zone but the effect would be adverse on local communities because of the multiplier effects[3] of lower production. The effect would be espeically

[3] See Osborn [7] for a description of these effects in the Southern portion of the Ogallala Zone.

adverse in the South Ogallala where there is a negative impact through backward linkages as the use of all inputs in the region is reduced. The full effect of a combined reduction in energy prices and equantities demanded would be especially adverse in a large part of the area where irrigation from the Ogallala Aquifer is currently practiced.

The amount of irrigated land converted to dryland because of the decline of the water table over the period 1977-1990 is found by comparing the amount of land in each water situation selected for 1990 by the model with how much land was in those situations in 1977:

$$LC = \sum_{p,l,w} L^*_{p,l,w,1977} - \sum L^*_{p,l,w,1990} \qquad (3)$$

where p = 55, 58, 63, 65, 72, 74 for the PAs; l = 1, 2, 3 for the land classes; w = 1, 2, . . . , 8 for the water situations, LC is the amount of land converted by 1990, and $L^*_{p,l,w,1990}$ is the amount of land in PA p, land class l, water situation w in 1990. Only land that is selected for irrigation by the model is used in Equation (3). The amount of irrigable land depleted therefore, depends in part on the economic conditions (alternative) that determine which situations can be profitably irrigated. The area of irrigated land depleted and converted to dryland in the entire Ogallala Zone is 1.05, 0.80, and 1.08 million acres for Alternatives I, II, and III respectively. The relatively small value for Alternative II is attributable to the smaller area it is profitable to irrigate for that alternative.

The area depleted by zone expressed as a percent of the area irrigated in each alternative is shown in Table 4. The area depleted in the South Ogallala is only 10.3 percent of the total irrigated land in this zone for Alternative I but jumps to 44.1 and 43.1 percent for Alternatives II and III, respectively. Nearly all land class I and II is selected for irrigation in Alternative I in this section of the aquifer. Nearly all of the area depleted is because of the thinning of the aquifer. However, the water table decline rates are greatest in this area and a large portion of area in 1990 is land with depths to water greater than 200 feet. It is not profitable to irrigate this land except in favorable economic conditions. Consequently, when these economic conditions are changed this land is not irrigated and is now shifted to dryland production. The estimate for the area depleted for the North and Central Ogallala tends to be more stable amounting to around 12 and 18 percent of the areas irrigated respectively for all three alternatives. The area depleted in these two zones is greatest in absolute terms for Alternative I because of the greater area selected for Irrigation in this alternative.

The effect of the depletion on the Ogallala Zone is important, of course, but nationally, the effect is nearly negligible. National production of Alternative I would be only 0.2 percent higher with no change in the water table assuming the same production practices are used on all land calsses and water situations as those in Alternative I. The effect on prices would also be very small. The analysis made for the effect of decline of the water table assumes production practices in the Ogallala Zone would not change qualitatively; the same production practices would be used in each land class and water situation but the number of acres in each production practice would change in proportion to the change in the land constraint.

The change in water use therefore follows very closely the changes in irrigated land use. But the effects on purchased inputs is less dramatic in relative terms. One reason why there is a smaller effect on purchased inputs is

TABLE 4. Changes in Resource Use in 1990 in the Oaallala Zone as a Result of the Mining of Groundwater, 1977-1990.

Zone	Alternative I	Alternative II	Alternative III
Irrigated Land Use			
North Ogallala	-11.7	-12.5	-11.2
Central Ogallala	-18.8	-18.4	-18.1
South Ogallala	-10.3	-42.3	-44.1
Water Use			
North Ogallala	-11.5	-12.9	-11.1
Central Ogallala	-18.9	-18.4	-17.8
South Ogallala	-10.3	-43.0	-44.1
Expenditures for Purchased Inputs[a]			
North Ogallala	-3.3	-1.4	-2.2
Central Ogallala	-2.0	-1.4	-1.8
South Ogallala	-3.7	-5.3	-15.9

[a]Includes ownership charges for capital assets but not land.

that the area that continues to be irrigated requires more inputs because water has to be pumped from greater depths. The effect of decreased demands alters production practices on all land because of the lower crop prices but the falling water table does not change production practices on dryland. The relative change in purchased inputs in the Zone therefore is smaller.

The effects of the fall in the water table on production and farm incomes are shown in Table 5. Again the effects are relatively small in relative terms. The effect on farm income especially is small because the farmers forced out of irrigation are those in the worse water situations, farmers whose income per acre with irrigation is very close to their income per acre with dryland because of high irrigation costs. The effects of production, farm income and on purchased inputs really appear to be a serious concern only for the South Ogallala Zone especially in Alternative III. The South Ogallala stands out in this instance because the change in production in this area is large in absolute as

TABLE 5. Effect in 1990 on Production and Sales, and Income from Farmland in the Ogallala Zone as a Result of the Mining of Groundwater, 1977-1990.

Zone	Alternative I	Alternative II	Alternative III
Production and Sales			
North Ogallala	-1.5	-0.7	-1.0
Central Ogallala	-1.0	-0.7	-0.8
South Ogallala	-3.7	-3.7	-9.4
Income from Farmland			
North Ogallala	-0.3	-0.2	0.0
Central Ogallala	-0.2	-0.1	-0.2
South Ogallala	-4.1	-1.1	-3.4

well as relative terms. A large area is irrigated in this zone and a larger proportion of the area is irrigated so the effect of the falling water table has more serious consequences on the local economy in this zone. Comparing Tables 2 and 5 however, it is evident that the seven percent decline in national demand or a doubling of energy prices has more far reaching implications even in this zone.

Conclusion

The effects of three qualitatively different phenomena on irrigation production and income in an area heavily dependent on groundwater irrigation have been examined. The difference in the phenomena is important; the fall of the water table by 1990 is a virtual certainty, a further doubling of real energy prices by 1990 seems very likely, but the level of demands is subject to greater uncertainty because of exports. However a rise in energy prices would bring about a *ceteris paribus* reduction in demand from levels that would otherwise be seen. The effect of reduced demands and the fall in the water table is very similar in all variables considered: irrigation is reduced, production sales and farm income all decline but the changes in the Ogallala Zone are much greater for the seven percent reduction in national demand in comparison to the changes resulting from decline of the water table. The effect of increased energy prices is more complex especially accompanied by decreased demands because there is substitution of other inputs for irrigation and production shifts out of the Ogallala Zone. Crop prices increase considerably which leads to higher farm incomes through increases in returns to farmland for all farmers; however, these benefits are not necessarily felt throughout the community. Production declines significantly with doubled energy prices throughout the Ogallala Zone and purchased inputs also decline in the South Ogallala. Business Activity dependent on agricultural commodities or in the South Ogallala with farm inputs would be diminished and in relative terms by amounts greater than changes due to the falling water table.

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