WRC RESEARCH REPORT NO. 38

ECONOMIC ANALYSIS OF WATER USE IN ILLINOIS AGRICULTURE

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FINAL REPORT

Project No. B-014-ILL

The work upon which this publication is based was supported by funds provided by the U.S. Department of the Interior as authorized under the Water Resources Research Act of 1964, P.L. 88-379
Agreement No. 14-01-0001-1497

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ABSTRACT

ECONOMIC ANALYSIS OF WATER USE IN ILLINOIS AGRICULTURE

Approximately 28,000 acres of field and specialty crops were irrigated in Illinois in 1966. Supplemental irrigation of corn accounted for over one half of this acreage. Important elements in the decision to invest in irrigation equipment for corn include the expected effect of irrigation on year-to-year fluctuations in income and on average income. Regression models were used to estimate the influence of moisture variables on corn yield. Moisture deficits were calculated using the season with the highest yield as a base. Although these models indicated a reduction in income variance as a result of removing moisture deficits by irrigation, they did not uniformly indicate an increase in average net income under irrigation. One of the regression models was then used as a basis for a dynamic programming analysis. A moderate gain in expected income from corn was obtained by employing the irrigation policy dictated by dynamic programming rather than the policy from a moisture-deficit model. The dynamic programming results were also superior to a commonly used rule of thumb for supplemental irrigation. In addition to the economic analysis of the irrigation of corn viewed as a single crop, it was necessary to examine its role in the context of the total farm business. The competitive position of corn in the rotation was evaluated and it was found that corn remained as an important crop after introduction of irrigation and consideration of the crop alternatives of snapbeans and cucumbers. Labor distribution was an important factor in determining an optimal cropping pattern. General rules were developed for adjusting leases on rented farms to provide economic incentives for both landlord and tenant to adopt supplemental irrigation. The results of all of the analyses would have been substantially improved with crop-response data from experiments in which the range of variation of water and complementary cultural practices included economically optimal levels of these inputs.

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ECONOMIC ANALYSIS OF WATER USE IN ILLINOIS AGRICULTURE
Final Report to Office of Water Resources Research, Department of the Interior, Washington, D.C., January 1971, 59 pp.
KEYWORDS--*economic analysis/farm management/*irrigation/corn/Illinois/linear programming/dynamic programming/crop response/cost analysis/regression analysis/soil moisture

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I. INTRODUCTION AND PROJECT OBJECTIVES

Crop production in Illinois, as everywhere else in the world, depends on water. Although precipitation is the primary source of moisture for plant growth, soil characteristics play a prominent role in determining the amount of moisture available for plant growth. During the crop growing season (April through September) the average precipitation in Illinois is about 22 inches, ranging from about 25 inches in the southern tip of Illinois to about 19 inches in certain areas of the northern part of the state. However, the loss of water from runoff is higher in the southern part of the state, thus making the amounts of moisture available for plant growth approximately equivalent throughout the state.

The most important crop in the state, corn, transpires about 10 to 14 inches of water for a 100-bushel crop. Evaporation from the soil requires an approximately equal amount of water. Given the state average of about 22 inches of precipitation during the growing season, there is adequate moisture, on the average, provided that the distribution of rainfall within the season is favorable and that runoff is not excessive. If below normal amounts of summer rainfall occur in combination with having less than a full recharge of soil moisture at planting time, serious reductions in corn yield may result. The frequency of such seasons is an important factor in determining the economic returns from supplemental irrigation of corn and other crops. Further, the adoption of new crop production techniques that increase yields and that are complementary with the water input tend to increase the water requirement for an economically optimal level of crop production.

The general objective of the research conducted under this project was to investigate methods for developing and interpreting information for making decisions, at the individual-farm level, regarding the use of water for the irrigation of crops in Illinois. The analysis of the results of a survey gave perspective and orientation to the other aspects of the project which dealt with analytical methods and their application to farm-level decisions, primarily with respect to the supplemental irrigation of corn.

Because supplemental irrigation may be viewed as a form of insurance, an important objective of the project was to estimate the effect of adoption of irrigation on the year-to-year variation in income as well as its effect on average income. Supplemental irrigation may prove attractive to some farmers if it provides a more stable income, even if the average income is reduced.

Investment in an irrigation system may have implications for the optimal cropping system, thus requiring an analysis of such investment within the context of the total farm business. The determination of the impact of irrigation on the competitive position of corn with respect to other crops, both irrigated and non-irrigated, was an important project objective.

Much of the farm land in Illinois is leased by the farm operator. If a new practice, such as irrigation, is to be adopted, the lease provisions must provide adequate economic incentives for both the landlord and the tenant. The final objective of the project was to develop appropriate lease provisions for cost-sharing on irrigated farms.

The six chapters which immediately follow represent, in general, the essential elements of one or more of the publications listed in Chapter IX of this report.

II. EXTENT OF IRRIGATION IN ILLINOIS

To determine the extent of irrigation in Illinois, a survey was conducted in the fall of 1966. County Extension Advisers in Agriculture sent questionnaires to every known irrigator in each county of Illinois. The response to the survey was not complete, but it does provide an indication of the trends of irrigation in the state. Of 162 questionnaires returned, 148 provided complete data.

Crops and Irrigation Methods

An estimated 28,000 acres of field and specialty crops were irrigated in 1966. Irrigators responding to the survey accounted for 21,444 acres. In Table 1 results of the 1966 survey are compared with results of a survey made in 1956. Corn, a favorite crop in both years, showed the greatest increase in acreage during the 10 years. Specialized crops (snap beans, other vegetables, sod, nursery items, flowers, and fruit) accounted for about 33 percent of the crops irrigated in 1956; 37 percent in 1966.

Table 1.--Illinois Crops Irrigated in 1956 and 1966; Acreages and Percent That Each Acreage Is of Total

Crop	1956		1966	
	Acres irrigated	Pct. of total	Acres irrigated	Pct. of total
Corn......................	2,823	42	12,335	58
Snap beans................	0	0	3,961	18
Other vegetables..........	1,111	16	1,827	9
Sod.......................	0	0	1,757	8
Soybeans..................	629	9	826	4
Hay and pasture...........	740	11	317	1
Nursery and flowers.......	726	11	214	1
Fruit.....................	394	6	207	1
Other.....................	343	5	---	---
Totals....................	6,766	100	21,444	100

Table 2 shows the acreages of various crops irrigated by different types of systems. The mechanized systems account for 52 percent of the acreage irrigated and the hand-move systems account for about 37 percent, leaving 11 percent divided between subsurface, surface, and solid-set systems. Of the 343 irrigation systems accounted for in the survey, 187 systems, or 55 percent, were hand-move; 140 systems, or 41 percent, were mechanized. The crops with the largest number of hand-move systems were corn and vegatables. Average acres per system were almost twice as much for the mechanized systems as for the hand-move systems.

Table 2.--Crop Acreages Irrigated by Each Type of System

Crop	Acres irrigated by each system[a]						Pct.
	Hand-move	Mechanized	Sub-surface	Surface	Solid set	Total	
Corn................	3,264	7,071	1,500	500	0	12,335	58
Snap beans.........	695	3,186	0	0	80	3,961	18
Other vegetables...	1,560	262	0	5	0	1,827	9
Sod................	1,317	25	0	0	415	1,757	8
Soybeans...........	422	404	0	0	0	826	4
Hay and pasture....	222	95	0	0	0	317	1
Nursery & flowers..	200	10	0	0	4	214	1
Fruit..............	197	0	0	10	0	207	1
Total...........	7,877	11,053	1,500	515	499	21,444	100
Percent.........	37	52	7	2	2	100	

[a] In hand-move systems, the pipes from which sprinklers operate must be moved by hand. Mechanized systems are all those with some type of self-propulsion across or around the field, including tractor-drawn tow-line systems. In subsurface systems, water permeates into the soil from buried tile line or small open ditches. Surface systems provide water by flooding and gravity flow down or between rows. A solid set system has enough portable laterals that they don't have to be moved. The laterals are placed in the field early in the season and remain until the last irrigation. The mains and submains may be either buried or portable.

Mechanization appears to be increasing in those areas of the state where labor is particularly hard to find, even though the initial cost of a mechanized system is higher than for a hand-move system. Almost two-thirds of the irrigators using hand-move systems with high labor requirements began irrigation before 1958; over 80 percent of the irrigators using a mechanized system began irrigation after 1958 (Table 3).

Table 3.--Irrigation Systems vs. Year Irrigation Began, 148 Irrigators[a]

Year irrigation began	Hand-move		Mechanized		Surface		Sub-surface		Total	
	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
Before 1954..	22	14.9	3	2.0	0	0	1	0.7	26	17.6
1954-58......	24	16.2	10	6.8	4	2.7	0	0	38	25.7
1959-63......	10	6.8	17	11.5	2	1.3	0	0	29	19.6
1964.........	5	3.4	4	2.7	1	0.7	1	0.6	11	7.4
1965.........	9	6.1	7	4.7	0	0	0	0	16	10.8
1966.........	2	1.3	26	17.6	0	0	0	0	28	18.9
Total.....	72	48.7	67	45.3	7	4.7	2	1.3	148	100

[a] Some irrigators had more than one system, but only the predominant system used by each irrigator was considered for this table.

Power Source

Internal combustion engines other than farm tractors accounted for about 65 percent of the total number of power units used. Farm tractors accounted for 23 percent; electric motors, 10 percent; and others, 2 percent.

Nearly half (49 percent) of the power units were gasoline engines, including automotive, industrial, and farm tractors; 21 percent were powered by LP-gas; 18 percent by diesel oil; and 10 percent by electricity. A possible reason why gasoline engines were the predominant source of power is that the irrigators best know how to operate and maintain such units. Also gasoline engines have a lower initial cost, although fuel costs are higher than for diesel engines.

Water Source

A total of 162 irrigators furnished data about their source of water. Wells provided the water for 17,527 acres, or 78.4 percent of the total irrigated acreage. With 174 wells in use, an average of 100.7 acres was irrigated per well. Natural streams provided the water for 7.2 percent of the acreage; constructed ponds and dugouts, 6.9 percent; drainage ditches, 6.4 percent; and other sources, including natural lakes and ponds, springs, and miscellaneous sources, 1.1 percent.

More than half (54 percent) of the wells were between 80 and 119 feet deep. One was less than 40 feet, and 12 were deeper than 220 feet. The diameter of 73 of the wells (42 percent) was 18 inches; 13 were greater than 18 inches in diameter; and the rest, 6 to 18 inches.

III. USE OF MOISTURE-DEFICIT MODELS TO ESTIMATE MEAN AND VARIANCE OF INCOME FROM SUPPLEMENTAL IRRIGATION OF CORN

Supplemental irrigation may benefit a farmer in two different ways--it may increase his average income and it may decrease the variability of his income over a period of years. Given a utility function which contains the arithmetic mean and the variance of income, a farmer contemplating investment in irrigation equipment should consider the effect of supplemental irrigation on both of these characteristics of the income probability distribution. Estimates of the values of these parameters will enable the farmer to evaluate the contribution of supplemental irrigation to his farming enterprise. The research reported in this chapter deals with a method of making these estimates and illustrates the results of using this method on data from experiments on the University of Illinois Agronomy South Farm combined with historical weather data.

Procedure

The procedure used is as follows:

1. Regression equations were fitted to estimate relationships between corn yield and various inputs, including, in Model I, available soil moisture and, in Model II, rainfall. These relationships were subsequently used to predict yields in a series of years, with and without irrigation.

2. The soil moisture level or rainfall pattern in the year with the highest predicted yield was designated as ideal. Assuming that the predicted maximum yield could have been obtained in any of the other years, had the corresponding level of moisture prevailed, a moisture

deficit was calculated for each year by subtracting the actual soil moisture or rainfall in that year from the rainfall in the "ideal" year. The moisture deficit is thus the difference between the actual moisture or rainfall in a year and a designated "ideal" moisture or rainfall level.

3. Yields were predicted under the assumption that the supplemental irrigation removed the moisture deficits. Thus, it is expected that the supplemental irrigation will result in yields as high as those of the best year. Moisture surpluses were allowed to have their effect on yield.

4. Input costs and corn prices were used to calculate the mean and variation of net income before and after irrigation. The "net income" is defined as the return above the cost of irrigation and, in the case of Model I, of the increased level of practices accompanying it.

Model I

The variables influencing corn yield investigated in this model are plant population, plant available soil moisture in a 17-day critical period including tasseling, and nitrogen applied. Basic data pertaining to corn yield and other inputs were provided by experiments conducted in 1958 and 1959 on Flanagan silt loam soil at the Agronomy South Farm at Urbana.

The following relationship was estimated:

$$
\begin{aligned}
Y = 47.2424 &+ \underset{(3.2362)}{3.8874}\,X_1 - \underset{(.6426)}{1.7055}\,X_2 \\
&- \underset{(0.3934)}{0.3479}\,X_3 - \underset{(0.1332)}{0.2951}\,X_1^2 + \underset{(0.0493)}{0.2831}\,X_1X_2 \\
&+ \underset{(0.0022)}{0.0030}\,X_3^2 + \underset{(0.0591)}{0.0513}\,X_1X_3 - \underset{(0.0002)}{0.0005}\,X_1X_3^2 \\
&- \underset{(0.0023)}{0.0013}\,X_1^2X_3 + \underset{(0.0044)}{0.0115}\,X_2X_3
\end{aligned}
$$

$R^2 = 73.9$

Standard error of estimate = 8.99 bushels,

$N = 192$.

Y is the bushels of corn per acre,

X_1 is the plant population (thousands per acre),

X_2 is the plant available soil moisture in the 17-day critical period (7 days before to 10 days after bloom stage), and

X_3 is the pounds of nitrogen applied per acre.

Keeping nitrogen and plant population constant at 75 pounds per acre and 16,000 plants per acre, yields for the period 1905 through 1962 were predicted. This required the estimation of plant available soil moisture (X_2) on May 1 for each of these years. Estimates were based on the total precipitation in the preceding seven months:

$$Y = 3.38 + 0.49X \quad (Y \leq 11 \text{ inches})$$

where Y is the inches of available soil moisture on May 1, and X is the inches of precipitation in the preceding seven months.

Yields, after supplemental irrigation, were predicted by holding the plant available soil moisture (X_2) constant at the ideal level of the year (1958) in which the highest yield occurred. The levels of nitrogen (X_3) and plant population (X_1) were elevated to 100 pounds per acre and 20,000 plants per acre, to accompany the higher and more certain soil moisture levels under supplemental irrigation.

The predicted yields with an ideal available soil moisture of 10.67 inches were 111.3 bushels per acre throughout the period 1905 to 1962. This constant yield was obtained because all the three independent variables in our regression equation (X_1, X_2, and X_3) were held at constant levels. However, the amount of irrigation water varied from year to year, depending on the moisture deficit.

Although the adoption of supplemental irrigation substantially reduced the year to year variance under this model (Table 1), the mean income actually declined. Higher levels of nitrogen and plant population to accompany the added moisture under the supplemental irrigation regime might have shown an increase in income. However, the experimental design did not permit increases of these inputs above the 100 pounds of nitrogen and 20,000 plant population.

Table 1. The Mean and Variance of Income Under Model I

	Before Irrigation (dollars)	After Irrigation (dollars)
Mean	92.90	90.06
Variance	152.20	18.35

Model II

The corn yield data used in this model are from an experiment on the Agronomy South Farm at Urbana in which a corn-corn-oats-clover rotation was followed from 1903 through 1956. Open pollinated corn was grown during the period 1903 through 1939, followed by hybrid corn.

In order to study corn yields for the period 1903-56, it was necessary to convert yields of the two kinds of corn to a comparable basis. Such a conversion was made by estimating the relation between the yields of open pollinated and hybrid corn in Illinois Corn Performance Tests and using this relation to convert open pollinated corn yields to their hybrid equivalent.

The tasseling date was chosen as the center of a 45-day period of analysis of the yield-moisture relationship. Five nine-day periods were considered. The tasseling date was calculated by accumulating degrees of maximum temperature above 56 degrees starting from the planting date until 1839 degree days were accumulated. This date was designated as the tasseling date and constitutes the middle day of the third period.

The following equation was fitted:

$$
\begin{aligned}
Y = {} & -680.32 + \underset{(0.11393)}{0.08319}T_1 + \underset{(0.16068)}{0.07574}T_2 \\
& -\underset{(0.14345)}{0.22612}T_3^L + \underset{(0.21099)}{0.59380}T_3^H + \underset{(0.10442)}{0.19568}T_4 \\
& -\underset{(0.12038)}{0.02641}T_5 + \underset{(10.20433)}{14.71818}P_1 + \underset{(10.66394)}{1.01832}P_2 \\
& +\underset{(11.20710)}{20.66392}P_3 + \underset{(7.60041)}{3.53213}P_4 + \underset{(11.09943)}{14.55468}P_5 \\
& -\underset{(3.54165)}{1.75266}P_1^2 + \underset{(2.51043)}{2.34162}P_2^2 - \underset{(3.09646)}{2.49677}P_3^2 \\
& -\underset{(1.84962)}{0.90444}P_4^2 - \underset{(4.14040)}{5.22919}P_5^2 - \underset{(0.16349)}{0.27256}I_1 \\
& +\underset{(0.24957)}{0.12749}I_2 - \underset{(0.18680)}{0.31403}I_3 - \underset{(0.40442)}{0.76880}I_4 \\
& +\underset{(0.30008)}{0.12293}I_5
\end{aligned}
$$

$R^2 = 0.657$,

Standard error of estimate = 15.66 bushels,

$N = 54$.

Y is the estimated bushels of corn per acre,

T_1, T_2, T_4 and T_5 are the sum of daily maximum temperature for the corresponding 9-day periods.

T_3^H is the temperature high for the tasseling interval; i.e., degree days of daily maximum temperature above 90°.

T_3^L is the temperature low for the tasseling interval; i.e. the degree days of daily maximum temperature less than 90°.

$P_1, \ldots, P_5$ are the amounts of total precipitation for the corresponding periods.

$P_1^2, \ldots, P_5^2$ are total precipitation terms squared for the corresponding periods.

$I_1, \ldots, I_5$ are the interaction terms for the corresponding periods.

The interaction term is defined as:

$$I_t = [\sqrt{P_t}\,]\ [T_t^H] \text{ for all } t.$$

Yields were predicted for each year in the period 1903 through 1956 by inserting the actual values of the explanatory variables into the equation. The highest predicted crop yield of 109.8 bushels occurred in 1948.

The moisture deficits for each period in each year other than 1948 were then calculated and these deficits were then assumed to be supplied by supplemental irrigation. Returns and costs were calculated for each year for both the non-irrigation and the irrigation system of corn production. These calculations were carried out in the same manner as for Model I except that Model II has no variables representing cultural practices. The results (Table 2) indicate an improvement in the average income and a decrease in variance as a shift is made from a non-irrigation to an irrigation system.

Table 2. The Mean and Variance of Income Under Model II

	Before Irrigation (dollars)	After Irrigation (dollars)
Mean	78.94	106.32
Variance	355.78	317.99

Summary

The results of Model I and Model II offer a sharp contrast. Model I has a marked reduction in variance because the year with the highest yield also had maximum available soil moisture in the 17-day critical period. This meant that there was no year-to-year variance in yield after the moisture deficit had been met. In contrast, the optimal rainfall levels in the five nine-day periods in Model II were frequently exceeded by natural rainfall. Thus, there remained a substantial variance in yield and also in income under irrigation.

The level of cultural practices in Model I was not high enough to capture all of the gains from irrigation. Even though cultural practices were omitted from Model II, there were net gains from irrigation. Apparently the response to rainfall when disaggregated into several periods and the consideration of the temperature-precipitation interaction more than offset the failure to take the complementarity of cultural practices with water into account. These mixed results indicate the need for experiments specifically designed to estimate the corn yield-water relationship along with estimates of the relevant interactions with cultural practices.

IV. A BREAK-EVEN ANALYSIS OF SUPPLEMENTAL IRRIGATION OF CORN ON A PIATT COUNTY FARM

A 470-acre cash-grain farm in east-central Illinois (Piatt county) was selected for the analysis. Each of three irrigation equipment suppliers was asked to design an irrigation system under the assumption that the entire farm would be in corn. The cost estimates from the three suppliers were then used to develop estimates of the increases in income necessary to justify supplemental irrigation.

Presently only a limited amount of information is available concerning the yield response of corn to supplemental irrigation, especially on heavy soils. Accordingly, specific recommendations cannot be made concerning the profitability of supplemental irrigation. However, estimates of the income increases necessary to pay for the investment and operation of a supplemental irrigation system should improve the basis for decisions on whether to irrigate corn.

Farm Description

The soils on this farm are predominantly Flanagan silt loam and Drummer silty clay loam. These soils were developed primarily from loess. They are dark colored, moderately permeable, with very good drouth resistance. When necessary, excess water can be removed by tile.

Because of the low-lying nature of the soils and their internal drainage characteristics, the possibility exists that in certain years with irrigation, yields would actually be reduced because of excess water, unless adequate tile drainage is provided. The tile system on the study farm is adequate to handle normal spring rains. Since supplemental irrigation will normally be used during the drier months of summer (July and August), it is assumed that this tile system will be adequate to remove excess water before crop damage occurs, should a heavy rain follow an irrigation cycle.

Method of Analysis

The analysis uses partial budgeting. This method considers only those items that change with a change in production technique. It is assumed that the entire farm will be in continuous corn both before and after adoption of supplemental irrigation. The added costs of certain changes in cultural practices in corn production are considered in the cost calculations.

The added costs directly associated with the addition of irrigation are presented in three categories--water source or well costs, pumping costs, and water distribution costs. Although costs for three different types of distribution systems are presented, the same well and pumping equipment are assumed to be used in each of the three systems.

Total added costs per acre are equated with the additional corn yield (at various prices) required to meet the cost of irrigation. The land area that must be taken out of production in order to operate the irrigation system is also considered. The break-even yield increase is thus adjusted for the loss in land acreage.

Cultural Practices

The only changes in cultural practices to be considered are increased plant population and fertilizer application. It is assumed that all other cultural practices are the same for both irrigated and nonirrigated corn. The increases in cost of weed control under irrigation were considered to be small enough to be ignored.

The present planting rate of corn is approximately 24,000 kernels per acre. This will be increased to 28,000 kernels per acre with irrigation. The extra cost is estimated to be $1.40 per acre.

Fertilizer application presently averages 150 pounds of nitrogen (N), 80 pounds of phosphorous (P_2O_5), and 90 pounds of potassium (K_2O) per acre. Soil tests indicate a moderately high soil supply of both phosphorous and potassium. With the addition of irrigation, it is assumed that nitrogen application will be increased 50 pounds per acre, phosphorous (P_2O_5) 20 pounds per acre, and potassium (K_2O) 30 pounds per acre. The added cost of this additional fertilizer is estimated to be $5.80 per acre.

Water Source and Cost of Well

Whether irrigation develops in a given area depends to a great extent on the availability of a large supply of water. The only source of water currently available for this farm is the ground water in the thick deposits of sand and gravel in the buried Mahomet bedrock valley which underlies the farm. The Illinois State Water Survey has indicated that a large capacity well approximately 300 feet deep could produce as much as 2,500 gallons per minute of water of a chemical quality that should be excellent for irrigation.

The cost of such a well is estimated to be $12,000. The estimate was obtained from a drilling contractor for a well 300 feet deep and capable of pumping 2,450 gallons per minute. The well is assumed to have a useful life of 50 years.

The estimated investment cost of the required pumping equipment is:

Double-drive pump.................	$ 6,908
Concrete base and installation....	460
Industrial engines, two , 220 BHP.....	3,380
Pump connections and fittings.....	149
Total.......................	$10,897

This is priced as designed by one of the irrigation companies. This company is a dealer for this equipment and also provides installation. Since this pumping equipment is part of the system that requires the highest pumping rate, it is assumed the equipment is adequate for the other two systems. The pumping equipment is assumed to have a useful life of 15 years, with a 10-percent salvage value.

Water Distribution System

Several assumptions are made in regard to the fixed costs of the water distribution field equipment for all three systems:

1. The purchase price includes installation or assembly.

2. A 5-percent sales tax is included.

3. The equipment has a useful life of 15 years with a salvage value of 10 percent of new cost.

4. Depreciation is figured by the straight-line method.

5. Interest is charged at the rate of 7 percent of average investment.

6. Insurance cost is assumed to be $0.60 per $100 of average value.

7. Personal property tax is computed using a 3.5-percent tax rate for 55 percent of average value.

8. No housing costs are included.

Variable costs associated with the actual irrigating operation include labor, fuel and oil for pumping, repair and maintenance, and any other variable cost necessary for operation. The labor requirements, hours of operation, and fuel costs are based on designers' estimates. Labor is charged at $2.00 per hour, fuel and oil for pumping at $3.50 per hour of actual operation. Repairs are charged at a fixed rate per acre-inch of water applied, with the rate depending on the type of equipment used. Tractor power is charged at $1.00 per hour of operation, which is the estimated variable cost of operation only.

Variable costs are approximate; exact figures depend on operator efficiency and organization. Variable costs per acre-inch of water applied also depend on the amount of water applied per irrigation cycle. For example, the total labor and tractor power required to move equipment would be approximately the same for a 2-inch application as for half that amount. Thus, with a 2-inch application the same labor and tractor costs are divided by twice as many acre-inches of water applied, and these costs per acre-inch are reduced by 50 percent.

<u>System A</u>. System A uses the "tow-line" principle. Normal installations of this type utilize a main line located in the center of the field. Long laterals run at right angles to the main, and are moved from setting to setting by disconnecting them from the main and using tractor power to tow the entire lateral across the main to a new setting on the opposite side of the field. Since the entire lateral is moved as a unit, moving time is reduced in comparison with the completely hand-moved system. Nevertheless, this system requires the most operational labor of the three systems. Sprinkler heads, positioned on high risers for irrigating tall crops such as corn, are located at

regular intervals on the lateral. Stabilizers on the laterals keep the risers in a vertical position.

The system designed for the study farm consists of six 1,960-foot lateral lines and six 1,280-foot lateral lines. The sprinklers are spaced at 40-foot intervals on the tow-lines. The distance between lateral settings is 60 feet. The system is designed to apply 2 inches of water to 406 acres in approximately seven and one-half calendar days.

Design capacity of System A is the highest of the three systems considered. It is designed to provide <u>all</u> the necessary water for the growing crop and as such is probably over-designed for supplemental irrigation in east-central Illinois. Because of the high water-holding capacity of soils in this area and the relatively large amount of rainfall during the growing season, a lower design capacity would probably be sufficient. This would reduce investment cost and consequently yearly fixed costs, while having little effect on the operational costs per acre-inch of water applied.

An estimated 60 hours of labor and 45 hours of tractor use are required per irrigation cycle. Eighty hours of pump operation are required to apply 1 inch of water to 406 acres and 160 hours to apply 2 inches.

System B. System B is a semi-automated system. A single, large-capacity sprinkler is mounted on a wheeled vehicle. The vehicle is positioned at one end of the field and a cable is run to the opposite end and anchored. An engine-winch on the vehicle winds in the cable and pulls the sprinkler slowly across the field. A plastic hose connects the sprinkler to the main which is located in the center of the field at a right angle to the direction of travel of the sprinkler vehicle. Size of sprinkler and speed of travel determine the rate of water application. Tractor power is required to move the vehicle between starting positions.

The system designed for the study farm consists of four individual units. It is designed to apply one inch of water to 460 acres in approximately 95 hours of actual pumping time. Successive lateral movements are 330 feet, which reduces the amount of land lost from production when compared with System A. However, distribution may be poorer, especially on windy days.

An estimated 41 hours of labor are required for a 1-inch application. An additional 4 hours of supervision time are included for a 2-inch application. Operational times for the pump are 95 and 190 hours, respectively, for the two levels of application.

System C. This system combines two types of equipment and is the most automated of the three systems. It consists of one large, self-propelled unit and two units similar to those of System B. The self-propelled unit involves a single, long lateral pipe supported by a series of wheels and towers. The entire assembly revolves slowly around a pivot point located in the center of the area to be irrigated. Water pressure is used to power the support wheels, which in turn rotate the system. Sprinklers are located at regular intervals on the lateral and vary in size according to the area of the circle that they must cover. The desired amount of water is applied in one revolution of the system. Rotational speed is variable so that application rates can be controlled. One disadvantage of the self-propelled system is that square corners cannot be irrigated.

The system designed for this farm includes a single, 1,673-foot self-propelled unit and two units of the System B type. The system as designed will apply 1 inch of water to 440 acres in approximately 90 hours of actual pumping time. Labor requirements are estimated at 22 hours per cycle for a 1-inch application and 26 hours for a 2-inch application.

Table 1.--Costs of the Three Systems

	Costs		
	System A	System B	System C
Investment per acre[a]..	$189.09	$171.93	$169.87
Fixed cost per acre[a]..	19.84	18.08	17.79
Variable cost per acre-inch, 1-inch application.........	1.19	1.05	1.03
Variable cost per acre-inch, 2-inch application.........	0.99	0.96	0.98

[a] Includes well, pumping equipment, and distribution system.

Costs of the Three Systems

Investment per acre and costs per acre for each system are presented in Table 1. One of the first things noticed when comparing the three systems was the similarity of investment costs, especially between Systems B and C. System A has the highest capital requirement, even though it is the most labor-intensive system. While this might appear as a discrepancy, it should be remembered that A has the highest design capacity which results in higher initial cost. System A is designed to meet all the necessary water requirements for the crop. This would only be necessary in a severe drought. System C is the most automated, but has the lowest initial cost. However, C utilizes an extremely large self-propelled unit (irrigating approximately 220 acres) which tends to reduce initial cost on a per-acre basis. If two smaller units were used in place of the single large unit, for the same number of acres, investment cost per acre would increase because of duplication of equipment.

Table 1 also illustrates an important point in regard to variable costs. For the 1-inch application, variable costs decrease slightly with increasing automation. However, with the 2-inch application most of this difference disappears. This fact is due largely to the effect of increased water application on labor and tractor costs per unit. In terms of total amount per irrigation cycle, these two costs are approximately the same for both rates of application. As the application rate per irrigation cycle is increased, the most labor-intensive system receives the greatest benefit in reduction of these costs on an acre-inch basis.

Break-Even Yield Increase

Because the costs of applying water are quite similar for all three systems, the average costs of the three systems are used in the break-even analysis. These averages are $18.57 fixed cost per acre, $1.09 variable cost per acre-inch for a 1-inch application, and $0.98 per acre-inch for a 2-inch application. The added variable costs for seed and fertilizer are also included.

The operation of most irrigation equipment requires land for turn strips, operational strips, or involves some crop damage. It is estimated that an average of 6 percent of the farmland is lost from production. Thus, the necessary extra production, or per-acre yield increase, must come from 0.94 of an acre.

Supplemental water added per acre is assumed to average 4 inches, applied in two 1-inch applications and one 2-inch application. For total water applications above or below 4 inches, only the variable cost of operation need be considered. For example, if an additional inch is applied, $1.09 is added to the total cost.

Table 2 summarizes the estimated additional costs that would be incurred if irrigation were added to this farm. Note that approximately two-thirds of the total costs are fixed costs and that the investment, once made, has a salvage value considerably below original cost. Table 3 gives the required yield increase necessary to break even at various prices of corn.

Table 2.--Per-Acre Cost of Irrigation, Assuming 4 Inches of Added Water

Annual fixed cost of added equipment.....	$18.57
Variable cost for two 1-inch water applications..........................	2.18
Variable cost for one 2-inch water application...........................	1.96
Added fertilizer cost....................	5.80
Added seed cost..........................	1.40
Total..................................	$29.91

Table 3.--Yield Increases Necessary to Break Even at Various Corn Prices[a]

Price of corn, dollars per bushel	Yield increase needed to break even, bushels
.90	35.4
1.00	31.8
1.10	28.9
1.15	27.7
1.20	26.5
1.25	25.5
1.30	24.5
1.40	22.7

[a] Assumes 6-percent field area loss, two 1-inch applications, and one 2-inch application.

Conclusion

The question of a realistic yield response to supplemental irrigation is complicated by the fact that there are few field experiments, combining irrigation and up-to-date cultural practices, currently being conducted in the Corn Belt. Most of those being conducted are on the more drouthy soils and lack direct applicability to the more drouth-resistant soils. Because of this lack of information on yield response, specific recommendations cannot be made from our analysis. However, the size of the needed yield increase gives some basis for making a judgment in specific farm situations.

During the seven-year period, 1961-1967, corn yields on this farm averaged 127 bushels per acre, ranging from 109.5 to 136.5 bushels per acre. This means that with corn at one dollar per bushel yields would need to be about 160 bushels per acre to break even under an irrigation program with 4 inches of water applied. Although such yields are reported in years with favorable weather, they reflect a high level of management in the form of timely application of carefully selected inputs. Such management is a critical factor in determining the success of an irrigation program.

Another factor entering irrigation decisions is the reduction of year-to-year variations in yields that should occur under irrigation. Some farmers may feel that this reduction is important enough to justify investment in irrigation even though there is loss in returns, on the average, under irrigation. In Section III of this report it was indicated that a decrease in year-to-year variations of net income may be expected with supplemental irrigation of corn.

Specialty crops such as green beans and cucumbers, in general, give higher returns than corn to investment in irrigation equipment. Where markets for these crops exist and appropriate soils are present, consideration should be given to including them in an analysis of the cropping system to determine the profitability of irrigation.

V. A LINEAR PROGRAMMING ANALYSIS OF IRRIGATION FARMING IN MASON COUNTY

In recent years there has been a marked increase in the area of irrigated land in the western half of Mason County. In 1959, 462 acres were irrigated on 9 farms. In 1969, 21,300 acres were irrigated on 114 farms. This adoption of irrigation is due to a number of reasons. The soils in the western section of Mason County are predominantly sandy, with a low water-holding capacity. This has caused very low crop yields in years of less than average rainfall; e.g., the average yield of corn in Mason County for 1966 was 69 bushels whereas the average yield for corn over the 10-year period 1959-1968 was 78.4 bushels.

Some farmers who started irrigating in the late 1950's and early 1960's found that irrigation could cause substantial increases in crop yields (especially corn) in most years. They found that irrigated corn could usually yield at least 110 bushels per acre, and, in years like 1966, irrigation could help to avert an economic loss.

Further, it was recognized that this part of Mason County possessed an almost unlimited supply of ground water at an average depth of 100 feet. This adequate supply of ground water, coupled with the development of automated irrigation equipment and its subsequent use as in Nebraska and the Dakotas, gave the physical means of delivering water to crops that would respond. Development of automated equipment is especially important in an area which has a restricted supply of labor. Another factor influencing the adoption of irrigation was the availability of contracts with canning companies for irrigators to grow vegetable crops (e.g., snap beans and cucumbers) which offered high, if somewhat variable, returns per acre. A successful double crop of snap beans would return $175 per acre net of variable costs.

It is obvious from the extent that it has been adopted in Mason County that irrigation is economically feasible and, in many cases, quite profitable. But there are still questions concerning the proportion of the farm to be irrigated and the best combination of crops. Because the answers to these questions depend on such factors as the yields and prices of crops, vegetable contracts available from canning companies, and the amount of labor available on the farm, the technique of linear programming is well suited to studying the economic consequences of alternative plans. Linear programming is a form of budgeting well adapted for use on computers so that a very large number of farm situations can be budgeted provided that the characteristics of the farm can be expressed mathematically.

In this study linear programming was used for a hypothetical farm in Mason County to determine the most profitable combination of crops for varying proportions of the farm irrigated, and, as a consequence, to measure the profitability of different sizes of irrigation equipment. The information upon which the characteristics of the farm depend was gathered from interviews with four irrigators and the extension advisor in Mason County. The results of several farm management studies performed by the Department of Agricultural Economics, University of Illinois also provided information.

The Model Farm

A hypothetical farm situation was developed which represented the important elements for decisions regarding crop combinations on irrigated

Four basic situations are considered:

(a) no irrigation;

(b) irrigated area of 150 acres;

(c) irrigated area of 287 acres;

(d) irrigated area of 437 acres (using both large and small systems).

The labor available on the farm is one full-time operator plus one full-time hired man for all or a part of the year. The hours of labor available from this supply are put at 480 per month except for May to August when they are put at 130 per week, with the proviso that the average should not exceed 120 hours per week for more than two consecutive weeks. This allows for peak periods during times of intensive cultivation.

Linear Programming Results

Using the above information and the linear programming procedure, farm plans which give the highest returns, net of variable costs, were determined for each irrigation situation. The plans consist of the acreage of each crop grown and the amount of labor used in each period (Table 2).

As irrigation equipment is increased, so the highest-return cropping plan changes. The first change (in going from the non-irrigated situation) is the introduction of high-value crops, snap beans and cucumbers. Because the net returns from cucumbers is slightly higher than snap beans, the maximum acreage (50 acres) of cucumbers permitted by the contract is grown in all plans with irrigation (Table 2).

farms in Mason County. This farm consisted of 470 acres of uniform land. The crops which could be chosen are given in Table 1 along with their planting and harvesting dates and quantities of water applied by irrigation. Livestock and pasture enterprises are not considered in order to simplify the study and also because irrigators indicated that decisions regarding irrigation do not affect livestock choices.

The crops are subject to rotational restrictions so as to minimize insect build-up. Because contracts for the vegetable crops are restricted, the maximum allowed in the model was 150 acres for snap beans and 50 acres for cucumbers (with the acreage of first and second crop being divided equally); this is in line with the size of current contracts. Prices and yields assumed for the various crops are also given in Table 1, along with variable costs (includes running costs for farm and irrigation machinery, fertilizer, seeds, and sprays).

The irrigation equipment chosen was the "Valley" type, which is the most automated available. However, the results are applicable to other types of automated equipment. The two sizes of Valley equipment most frequently used in Mason County are the 40-acre size (irrigates 37.5 acres) and the 160-acre size (irrigates 143.5 acres).

The 40-acre system can apply 1 acre-inch per week to a 160-acre (effective irrigated area is then 150 acres) field by using it from four watering points. Likewise, the 160-acre system can apply 1 acre-inch per week in two adjacent 160-acre fields (effective irrigated area is 287 acres).

Table 1.--Crops Grown on 470-Acre Model Farm, Mason County, Illinois

	Corn	Irrigated corn	Soybeans	Irrigated soybeans	Soybeans second crop	Wheat	Snap beans		Cucumbers	
							First crop	Second crop	First crop	Second crop
Planting dates	May 8-23	May 8-23	May 20-25	May 20-25	July 15-22	Oct.	May 7-15	July 23-31	May 7-15	Aug. 1-8
Harvesting dates	Sep. 29 -Nov. 7	Sep. 29 -Nov. 7	Sep. 23 -Oct. 6	Sep. 23 -Oct. 6	Sep. 23 -Oct. 6	July 7-11	July 7-15	Sep. 23-30	July 7-15	Oct. 1-8
Irrigation										
June (inches)	--	--	--	1.0	--	--	4.0	--	3.0	--
July (inches)	--	4.0	--	1.0	0.5	--	1.0	--	1.0	--
August (inches)	--	4.0	--	1.0	2.0	--	--	2.0	--	2.0
September (inches)	--	--	--	--	0.5	--	--	1.0	--	1.0
Total (inches)	--	8.0	--	3.0	3.0	--	5.0	3.0	4.0	3.0
Yield (bushels per acre)	75	130	30	40	20	35	(a)	(a)	(a)	(a)
Price (dollars per bushel)	1.00	1.00	2.40	2.40	2.40	1.40	(a)	(a)	(a)	(a)
Gross returns (dollars per acre)	75.00	130.00	72.00	96.00	48.00	49.00	100.00	100.00	100.00	100.00
Variable costs (dollars per acre)	18.32	32.61	12.22	18.11	10.69	12.50	27.75	25.63	19.24	21.96
Net returns (dollars per acre)	56.68	97.39	59.78	77.89	37.31	72.25	72.25	74.37	80.76	78.04

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[a] Yields and prices are not used for these crops; the canning companies pay the farmer a return per acre based on yield, quality and price of the crop.

As the acreage irrigated increased, irrigated corn became more important, reaching a maximum of about one-half of the cropped area when 437 acres are irrigated. At this level of irrigation, the only dryland activity was wheat; the area of soybeans decreased from 131 acres, with no irrigation equipment, to 10 acres of full-season soybeans being irrigated plus 55 acres of irrigated soybeans following wheat.

It should be noted that the area of snap beans never reaches its contract limit of 150 acres. Even if cucumbers were removed from the cropping alternatives (there were no cucumber contracts in 1969) and this acreage made available for snap beans, the snap bean acreage would still remain at less than its contract limit of 150 acres. In general, vegetable crops with similar cultivation and return characteristics to snap beans would occupy less than one-third of the cultivated area. This indicates a somewhat stronger competitive position for corn than might be expected.

What causes this limitation on vegetable crops? The answer is not apparent in the presentation of figures for labor used (Table 2). It will be remembered that labor available on the farm was specified as 130 hours per week during the period of intensive cultivation, with a proviso that the average should not exceed 120 hours in consecutive weeks. Behind the monthly totals in Table 2 are weekly labor figures. For all irrigation situations, the limit of 130 hours is reached in at least one week--e.g., for 437 acres irrigation, 130 hours are used in the second week of May and first week of June. Thus, the shortage of labor in these periods prevents an increase in the area of vegetable crops.

Table 2.--Highest-Return Farm Plans for Various Sizes of Irrigation Equipment, 470-Acre Farm, Mason County, Illinois

Area irrigated (acres)	0	150	287	437
Net return[a]	$24,518	$37,164	$45,342	$49,964
Crops (acres)				
Corn	214	135	--	--
Irrigated corn	--	50	140	233
Soybeans	131	111	113	--
Irrigated soybeans	--	--	--	10
Soybeans (second crop)	--	--	--	(55)[b]
Wheat	125	74	70	88
Snap beans (first and second crops)	--	50	97	89
Cucumbers (first and second crops)	--	50	50	50
Total	470	470	470	470
Labor used (hours)				
January	53	54	58	64
February	53	54	58	69
March	200	204	185	212
April	184	284	337	369
May	332	455	452	424
June	232	313	344	324
July	236	281	328	396
August	116	226	296	350
September	171	200	192	174
October	480	383	363	51
November	89	99	94	124
December	24	34	38	40
Total	2,170	2,587	2,745	2,987

[a] Gross returns minus variable costs.

[b] Not included in total because it is grown on land following wheat.

Now it might be argued that if the labor in the first, third, and fourth weeks of May and the second week of June is not fully utilized, some cultivation could be shifted from the second week of May to the first week of June. Careful examination of the weekly labor figures shows the average amount of labor required for the six-week period, late April to early June, is 120 hours per week, and this is the maximum labor assumed to be available from two full-time men.

Some further comments are required on the labor figures. The monthly distribution is very uneven with little labor used in January, February, November, and December; this may appear as inefficient use of labor. But idle labor in these months may be the price that has to be paid if the men are expected to work a sixty-hour week for some periods of the year. If the operator has an opportunity to hire full-time labor for the period in which crops are grown, this is preferable to hiring a man for the entire year. It will be recalled that livestock are not considered as a part of the farm activities.

The Effect of Changes in Yields or Prices

Because of uncertainty regarding the yields and market prices of various crops, it is reasonable to ask to what extent do the highest-return plans produced by linear programming remain optimal when uncertainty is considered. To partially answer this, an examination was made of the effect of changes in per-acre returns of the vegetable crops. By further programming, we can produce optimal farm plans for the reasonably expected range of returns for snap beans and cucumber crops. These plans are given in Table 3 for the situation of 287 acres of irrigated land.

Table 3.--Highest-Return Farm Plans with Varying Snap Beans and Cucumber Returns; 470-Acre Farm (287 Acres Irrigated) Mason County, Illinois

	Returns per acre, snap beans and cucumbers[a]				
	$100	$120	$140[b]	$180[c]	$300
Net returns	$34,994	$35,582	$36,719	$42,432	$62,057
			Acres		
Corn	--	--	35	--	--
Corn (irrigated)	241	236	145	140	74
Soybeans	70	95	91	113	98
Soybeans (irrigated)	36	--	--	--	45
Soybeans (second crop)	--	16[d]	4[d]	--	--
Wheat	113	104	61	70	85
Snap beans	6	32	88	97	118
Cucumbers	4	3	50	50	50
Total	470	470	470	470	470
			Hours		
Labor used, total	2,438	2,575	2,773	2,750	2,779

a Returns are for first plus second crop.
b The plan for $160 is same as for $140.
c Plans for $200 and $280 are the same as for $180.
d Not included in total.

The farm plans in Table 2 assume gross returns of $200 per season ($100 per crop) for snap beans and cucumbers. The plan for the 287-acre irrigation situation was optimal over a range of returns from $180 to $280 per acre per season and was little different in terms of acreage of vegetable crops from the plan which is optimal for $140 and $160. That is, if the returns for vegetable crops are expected to fall mainly in the range of $140 to $280 per acre, the optimal strategy is to plant between 138 and 147 acres of these crops.

A similar analysis for varying gross returns per-acre from irrigated corn revealed that the farm plans in Table 2 which assumed gross returns of $130 per acre (130 bushels per acre at $1.00 per bushel) remained optimal over a range from just below $130 to just below $170 per acre. Again, if returns are expected to fall mainly within this range, then the best strategy is to grow 140 acres of irrigated corn.

Profitability of Irrigation Equipment

One method of measuring this is to compare the increased returns due to irrigation with the capital cost of the irrigation equipment used (Table 4). The first step was to compare each of the three irrigation situations with the no-irrigation situation; this showed that investment in any of the three irrigation systems will yield more than 30 percent return on capital. Of course, this assumed that the prices and yields (Table 1) are actually experienced and that the highest-return plans are followed.

The story is a little different if we consider the profitability of each irrigation situation in relation to the others (Table 4).

Table 4.--Analysis of Profitability of Irrigation Equipment

	Acres irrigated			
	0	150	287	437
Capital cost of irrigation equipment[a]....	0	$26,860	$34,260	$61,130
Annual overhead cost[b]	0	2,686	3,426	6,113
Net return for farm plan.................	$24,518	37,164	45,342	49,964
Net return minus overhead...............	24,518	34,478	41,916	43,851
cf. 0 irrigated acres				
A. Increased investment...................		26,860	34,260	61,130
B. Increased net return...................		9,960	17,398	19,333
B/A (percent)[c]		37	51	32
cf. 150 irrigated acres				
C. Increased investment.............................			$7,400	$34,270
D. Increased net return.............................			7,438	9,373
D/C (percent)[c]..................................			100	27
cf. 287 irrigated acres				
E. Increased investment..				$26,870
F. Increased net return..				1,935
F/E (percent)[c]				7

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[a] This includes cost of well, pump, motor, irrigation machinery, pipes and all installation.

[b] Estimated at 10 percent of capital cost; 9 percent for depreciation and 1 percent for taxes and insurance.

[c] Rate of return on added investment.

One can interpret the results in the following way. If a farmer is considering introducing irrigation to his farm, and if there is no limit on availability of funds at market interest rates, he would increase returns by buying equipment to irrigate 287 acres rather than 150 acres; if he were considering investing approximately $27,000 in the smaller set of equipment, then by adding $7,000 more of equipment he would be earning 100 percent on this added investment.

If he has decided to install equipment to irrigate at least 287 acres, should he add the 150-acre system and irrigate 437 acres? This extra investment of approximately $27,000 is seen to yield a return of only 7 percent, and the farmer may be somewhat doubtful, given a 10-year depreciation period, of such an investment.

A word of warning about the interpretation of these figures. If a farmer actually had 150-acre equipment and was considering increasing his irrigated area, the only way he could do this (in terms of this study and assuming the 150-acre equipment cannot be traded in for 287-acre equipment) would be to buy 287-acre equipment to irrigate 437 acres. The return on this added investment is 27 percent.

The foregoing analysis assumes a two-man labor supply available and that labor costs are the same for all situations. In specifying the labor supply, we stated that a full-time operator plus a full-time man were available for all or part of the year.

The hired man might be employed only for that part of the year when his labor is required. This means six-month employment when there is no irrigation and seven months for the three irrigation situations (Table 2). Assuming that the hired man is paid $400 per month, this will lower the returns to irrigation investment by about one percentage point for the three irrigation situations, compared with no-irrigation situation. For the purposes of this analysis, the increased labor required in going from one irrigation situation to another can be thought of as being supplied by the operator.

VI. A DYNAMIC PROGRAMMING ANALYSIS OF SUPPLEMENTAL IRRIGATION OF CORN

The previous analyses in this report have abstracted from two important aspects of the decision-making process regarding irrigation. During any given crop season decisions about the quantity of water to be applied in each of the periods are made sequentially. That is, the amount of water to be applied in any period within the growing season depends on the condition of the crop and/or soil moisture at the beginning of that period. Further, the results of such an application in terms of its effect on yield are probabilistic in the sense that they depend on such climatic variables as the amount of natural rainfall and temperatures occurring during the period. The moisture-deficit method used in Chapter III of this report does not view the within-season decisions regarding irrigation as being sequential. Rather, the amounts applied are those which make total water applied (natural rainfall plus supplemental irrigation) identical with natural rainfall in an "ideal" year. Although the year-to-year variance of returns was estimated, the probabilistic nature of the yield outcomes of various levels of irrigation in individual periods was not considered. The linear programming analysis of Chapter V considered a single within-season pattern of the irrigation of corn for comparison with a no-irrigation regime for corn and other crops, both irrigated and non-irrigated. However, the linear programming model is non-probabilistic and thus does not take into account an important feature of decisions regarding supplemental irrigation of corn. The method of dynamic programming views the decision-making process as both sequential and probabilistic and thus provides a somewhat more realistic model.

In this chapter the results of the use of a dynamic programming model are presented and compared with those of a moisture-deficit model and a commonly used rule of thumb for supplemental irrigation.

The Method of Dynamic Programming: An Example

A hypothetical example will illustrate the basic features that characterize the empirical application of dynamic programming to the supplemental irrigation of corn. Assume that a particular initial state (crop condition) at the beginning of June (period 1) is given. An initial decision concerns the application of irrigation water during the first period. Irrigation is assumed to cost \$3.00 per acre. Depending on this initial decision, a transition to any of the three states, i.e., good crop, medium crop, or poor crop is possible in July (period 2). These transitions are governed by a set of probabilities (Table 1).

Table 1 Possible Irrigation Strategy in June (period 1) and Resulting Transitions to July (period 2).

	Transition Probabilities		
Alternative in June	Good crop in July	Medium crop in July	Poor crop in July
Irrigation	0.6	0.3	0.1
No Irrigation	0.3	0.4	0.3

The irrigator must also decide whether to irrigate in July (period 2). At the time this decision is made, the state of the crop at the end of period 1 (beginning of period 2) is known as well as the probability of obtaining each specified terminal reward (end of period 2) under each of the two irrigation alternatives.

Table 2 Transition Probabilities and Terminal Rewards in July (period 2).

State	Alternative	Returns net of harvest costs $60	 $70	 $80	 $90	 $100
Good crop	1 Irrigation	0.0	0.1	0.2	0.4	0.3
	2 No Irrigation	0.1	0.2	0.3	0.3	0.1
Medium crop	1 Irrigation	0.1	0.2	0.4	0.3	0.0
	2 No Irrigation	0.2	0.3	0.3	0.2	0.0
Poor crop	1 Irrigation	0.2	0.3	0.4	0.1	0.0
	2 No Irrigation	0.2	0.4	0.4	0.0	0.0

In order to maximize the total expected earnings, the irrigator wishes to know whether to irrigate in each period. Using the backward multistage problem-solving approach, our solution procedure begins in period 2. Here we look at the states good crop, medium crop, and poor crop in an attempt to determine an optimal strategy for irrigation application in this period.

The maximum expected return for each of the three crop conditions at the beginning of period 2 can be determined by a comparison of expected returns with and without irrigation:

Good Crop

$$\text{Irrigation: } \left[(0)(60) + (0.1)(70) + (0.2)(80) + (0.4)(90) + (0.3)(100) - 3\right] = \$86.00$$

$$\text{No irrigation: } \left[(0.1)(60) + (0.2)(70) + (0.3)(80) + (0.3)(90) + (0.1)(100) - 0\right] = \$81.00$$

Irrigation gives higher expected return.

Medium Crop

Irrigation:
$$\begin{aligned}&[(0.1)(60) + (0.2)(70) + (0.4)(80) + (0.3)(90)\\&+ (0.0)(100) - 3] = \$76.00\end{aligned}$$

No irrigation:
$$\begin{aligned}&[(0.2)(60) + (0.3)(70) + (0.3)(80)\\&+ (0.2)(90)] = \$75.00\end{aligned}$$

Irrigation gives higher expected return.

Poor Crop

Irrigation:
$$\begin{aligned}&[(0.2)(60) + (0.3)(70) + (0.4)(80) + (0.1)(90)\\&+ (0)(100) - 3] = \$71.00\end{aligned}$$

No irrigation:
$$\begin{aligned}&[(0.2)(60) + (0.4)(70) + (0.4)(80)\\&+ (0)(90) + (0)(100)] = \$72.00\end{aligned}$$

No irrigation gives higher expected return.

The results are summarized in the following table:

Table 3 The Expected Net Returns and the Optimal Irrigation Policies of the Sequential Problem in July (period 2).

State	Policy Decision	Expected Net Returns
Good crop	Irrigation	\$86.00
Medium crop	Irrigation	\$76.00
Poor crop	No Irrigation	\$72.00

The procedure now moves back to the first period and considers the following question. Assuming adoption of the optimal decision in period 2, what is the most profitable irrigation alternative in period 1? Here again, we evaluate the expected return for each of the two policy choices--irrigation or no irrigation. However, since there is only a single crop condition at the beginning of period 1, as contrasted to three crop conditions (states) at the beginning of period 2, only two expected returns need to be calculated. Note that the higher expected return calculated above for each of the crop conditions at the beginning of July is used: (Irrigation of good crop) \$86.00 rather than \$81.00, (Irrigation of medium crop) \$76.00 rather than \$75.00, and (No irrigation of poor crop) \$72.00 rather than \$71.00. The appropriate transition probabilities are selected from Table 1.

Irrigation: $[(0.6)(86) + (0.3)(76) + (0.1)(72) - 3] = \$78.60$

No irrigation: $[(0.3)(86) + (0.4)(76) + (0.3)(72)] = \$77.80$

The higher expected returns come from irrigation in period 1. Thus, the optimal choice for June is irrigation, under the assumption that an optimal policy is followed in July. At the beginning of July, crop conditions are evaluated and the desirability of irrigation (Table 3) depends on this evaluation and the transition probabilities to the terminal reward.

Application of Dynamic Programming to Agronomy South Farm Data

The same basic procedure outlined above was used to evaluate within-season supplemental irrigation policy for corn. The analysis used the same set of data as that used for Model II of Chapter III. In order to represent the "state" or crop condition at the beginning of each of the periods as a value of a single variable and to thus make the dynamic programming approach manageable, the composite variable, U, was formed as follows:

$$U = \sum_{t=1}^{5} (a_t P_t + b_t P_t^2 + c_t I_t)$$

where the variables have the same definitions as Model II in Chapter III. It will be recalled that there are five 9-day periods with the center of the third period being the tasseling date. A non-linear least-squares estimation procedure was used to estimate parameters in the following function which contains the same variables as Model II of Chapter III, but with the 15 terms indicated above appearing in U and U^2:

$$\begin{aligned} Y = {} & -689.23 + 1.2836U + 0.0010U^2 + 0.0838T_1 \\ & + 0.0723T_2 - 0.2287T_3^L + 0.6034T_3^H \\ & + 0.1998T_4 + 0.0027T_5 \end{aligned}$$

The definition of the last six terms, which are temperature variables, are the same as in Model II of Chapter III. The standard errors of the regression coefficients as well as the standard error of estimate are higher in this equation than with the linear least-squares results for Model II of Chapter III. The coefficient of U failed to be significantly different from 1.0 and the coefficient of U^2 did not differ significantly from zero. Consequently, the analysis proceeded with Model II of Chapter III with the precipitation terms and the temperature-precipitation interaction terms being aggregated into the crop condition variable, U, as defined above. Use of this simpler model without the U^2 term, implies that, in the absence of constraints on water supply, optimization of the level of supplemental irrigation in each of the five periods could be performed independently of the irrigation levels in the other periods.

Five levels of supplemental irrigation were considered for each period: 0.0, 0.5, 1.0, 1.5, and 2.0 acre-inches. Values for the crop condition indicator, U, for each period were calculated for each of these five levels. The number of state values considered differed for each period. At the beginning of the first period, only a single crop condition was considered, while at the end of the fifth period, 76 values of the crop condition were considered. The probabilities of transiting from a given state in a given time period to states in the succeeding time period were estimated from historical weather data.

Summary of Results With Comparisons

The optimal levels of supplemental irrigation indicated by the dynamic programming analysis are presented in Table 4. Note that the maximum level considered, 2.0 acre-inches, is optimal in all periods except the third. This set of optimal policies requires a greater quantity of water than policies derived by other methods. The "actual moisture deficit" column in Table 4 refers to Model II of Chapter III. Estimation of irrigation water applications under this model assumed that any amount of water might be applied, ranging from none to that amount which occurred as natural rainfall in that period in the "ideal" year. The water applications reported in Table 4 for the models other than dynamic programming are <u>average</u> applications over the 54-year period. In order to provide a more appropriate comparison with the dynamic programming results, an adjusted moisture deficit model was used in which the same general procedure was followed as with the actual moisture deficit model but considering the irrigation levels to be restricted to zero and the range from 0.5 to 2.0 acre-inches. This adjustment reduced the optimal level of water application in the fourth period. Finally, the results of a rule of thumb were calculated. This rule requires the application of an inch

Table 4 Optimal Operating Policies for Corn Irrigation in East-Central Illinois

Period	Period in relation to tasseling date	Supplemental Water Added Under			
		Dynamic Programming	Actual Moisture Deficit	Adjusted Moisture Deficit	Rule of Thumb
		(Acre Inches)			
1	22 to 14 days before tasseling	2.00	0.65	0.62	0.59
2	13 to 5 days before tasseling	2.00	2.54	1.77	0.66
3	4 days before to 4 days after tasseling	1.5	0.89	0.83	0.70
4	5 days to 13 days after tasseling	2.00	0.11	0.04	0.61
5	14 to 22 days after tasseling	2.00	0.53	0.50	0.66
	Total supplemental irrigation during the critical 45-day period	9.5	4.72	3.76	3.24

of water during each 9-day period in which less than an inch of rain falls.

The economic results are presented in Table 5. These results are based on a net corn price of $1.13 per bushel,irrigation water at $1.00 of variable cost per acre-inch, and $20.00 per acre of fixed cost for irrigation equipment.

Table 5 Effect of Supplemental Irrigation on Mean Income From Corn: A Comparison of Results

Model	Mean Income ($ per acre)	
	Before Irrigation	After Irrigation
Actual moisture deficit	$78.94	$106.32
Adjusted moisture deficit	78.94	92.69
Dynamic programming	78.94	98.28
Rule of thumb	78.94	74.20

The actual moisture deficit model gives the highest return. However, it should be noted that this model is not restricted to applications of two inches or less. For the adjusted moisture deficit model this limitation is imposed, along with the requirement that irrigation must be at either zero, if the moisture deficit were less than 0.5 inches, or any amount in the range from 0.5 to 2.0 acre-inches. The results from this model indicate a lower return than with the dynamic programming model. Thus, when comparable assumptions are used, there is an improvement in returns by following the dynamic programming policy. Further, the information requirements of the dynamic programming model are less than that of the moisture deficit model and the rule-of-thumb model. The dynamic programming model assumes knowledge of the condition of the crop at the beginning of the period, and the transition probabilities that relate the crop condition in any given period to its condition in the subsequent period under a range of irrigation policies. In contrast, the moisture deficit and rule-of-thumb models assume that the natural rainfall occurring during the period is known exactly over the range which would require application.

In summary, the dynamic programming results represent an improvement over comparable models. The estimates of increases in income from all models would probably have been increased with the use of a production function with more accurately specified inputs at ranges which would include their important interaction effects with water.

VII. LEASING ARRANGEMENTS FOR IRRIGATION FARMING

Although supplemental irrigation is being used primarily on land owned by the operators, a significant number of farmers are irrigating rented land. The survey mentioned in Chapter II indicated that twenty-nine of the sample of 76 complete records were irrigating rented land. Seventeen of these had rented land only. Of these seventeen, three paid cash rent, and one had a combination of cash and share rent. Two farms gave one-third of the crop as rent, four gave two-fifths, and seven gave a half-share as rent. Data for the latter two groups of farms are shown in Table 1.

Table 1.--Sharing Arrangements for Irrigation Investments and Costs on Rented Land, by Share of Crop Given as Rent.

Items	1/2 rent share		2/5 rent share	
Number of farms	7		4	
Acres irrigated	121		141	
Acre-inches of water per crop acre	5.81		7.21	
Investments per farm:	Tenant	Landlord	Tenant	Landlord
Water sources	$ --	$ 818	$ --	$1,410
Pump and motor	1,735	1,435	3,150	1,950
Distribution system	2,829	7,186	10,546	3,238
Total investment	$4,564	$9,440	$13,696	$6,598
Fixed costs per crop:				
Depreciation	$ 2.42	$ 4.65	$ 6.05	$ 2.48
Interest	1.75	4.15	6.35	3.06
Property taxes	.32	.77	1.18	.57
Total fixed cost	$ 4.49	$ 9.57	$ 13.58	$ 6.11
Operating costs per crop acre:				
Fuel and electricity	$ 3.37	$ 1.17	$ 4.19	$ .62
Repairs and other	.69	.64	.13	--
Labor	3.36	--	1.86	--
Total operating costs	$ 7.42	$ 1.81	$ 6.18	$ .62
Total annual costs per crop	$ 11.91	$ 11.38	$ 19.76	$ 6.73
Percent by each party	51%	49%	75%	25%

Given the conditions for a profitable investment in supplemental irrigation on a total-farm basis, our question is, "How should irrigation costs be shared between tenant and landlord on rented land"?

A general principle in farm leasing is to share total inputs in the same ratio as the crops produced are shared. Unless this is done, one party will be receiving a lower return on his inputs than the other party and he will therefore not cooperate in adopting a new practice such as supplemental irrigation, or he will do so at an economic disadvantage.

Leasing Guidelines

Prevailing custom for rented farms in the areas where supplemental irrigation is being adopted requires that the landowner furnish or pay for all items that are or will become a part of the real estate. This means that the cost of a well, or reservoir, and the pump should be the landlord's contribution. Further, it is customary that the labor to operate the farm and the irrigation system is furnished, or paid, by the tenant.

All other costs can then be shared in such a way as to achieve the same share of <u>total</u> costs as each party receives of the crops grown. This reduces to three basic questions:

(1) Who should furnish the capital investments in (a) the motor on the pump, and (b) the distribution system?

(2) Who should pay fuel and electricity costs to operate the system?

(3) Who should pay for ordinary repairs?

The rule on repairs may well be to share them in the same way as the crop is shared even though the item, such as the pump, is owned entirely by the landlord. An exception to this rule would be repairs on the motor. These should be the tenant's contribution. Then he is free to choose between extensive repairs or replacing the motor.

Sharing in repairs on the pump and distribution system will give the tenant an incentive to be careful in the use of the landlord's property where the landlord furnishes part or all of these items. If the landlord does not furnish any of these items, he should not share in the repair costs.

Fuel and power costs are a flexible item. They may be shared or they may be paid entirely by the operator. The incentive condition in the latter case is no problem if both parties agree on when and how much water to apply independently of who pays these operating costs. This, then, leaves the question of who contributes what amount to the investments in a motor, or power source, and the distribution system.

Because of its vulnerability to careless management, the motor may well be the tenant's sole responsibility. This not only puts the incentive for proper care where it should be but it leaves the tenant free to use his farm tractor as a power source if he so chooses.

The investment in the distribution system thus becomes the principal item for adjusting contributions between the two parties. Possibilities range from the landlord furnishing total investment to the tenant furnishing total investment. Depreciation interest and property taxes are fixed costs which will be proportional to the original investment by each party.

Application of Guidelines

A hypothetical situation may now be compared with the actual experience reflected in the averages for the two groups of farms in Table 1. The data in Table 2 are based on estimated values for a self-propelled distribution system covering about 165 crop acres with approximately 6.5 inches of water each year. This table provides an illustration of how contributions by each party may be estimated and adjusted to fit the rent share rather than adhering to a rigid cost-sharing pattern.

The analysis in Table 2 assumes that the landlord always furnishes the water source and pump and that the tenant always furnishes the motor and all labor. All other costs and investments are shared the same way as the crop is shared. The result is a total cost-sharing as indicated on the bottom line of the table.

One important additional assumption must be noted in using Table 2 and the principles employed in it. This is the assumption that the rent-share which was found acceptable before going to supplemental irrigation will continue to be used after irrigation has been adopted. It can be argued that, by increasing his contributions through investments in irrigation capital, a landlord may earn a larger share of the crop as rent. For example, the one-third share landlord may feel his added contributions will now earn a two-fifths rent share, or a two-fifths share landlord may feel his property is worth a one-half rent-share under irrigation. Such increases in rent-shares will be justified only if the landlord's irrigation contributions are large enough to bring his total farm contributions up to the new level for all crop costs. This condition is not likely to be met unless the landlord's relative irrigation contributions equal or exceed those expected from a one-half rent-share landlord. It is to be understood, of course, that any shift to a higher rent-share automatically obligates such a landlord to the same higher share in such costs as fertilizer, crop seeds, pesticides, and combining.

Table 2.--Models of Cost and Investment Sharing for Supplemental Irrigation by Share of Crops Paid as Rent. Hypothetical Data Assuming a Self-Propelled Distribution System Irrigating About 165 Crop Acres With About 6.5 Inches of Water Applied per Acre.

Items	Total farm	1/2 rent share		2/5 rent share		1/3 rent share	
		Tenant	Landlord	Tenant	Landlord	Tenant	Landlord
Investments:							
Water source	$ 2,100	$ 0	$ 2,100	$ 0	$ 2,100	$ 0	$ 2,100
Pump	2,500	0	2,500	0	2,500	0	2,500
Motor	2,000	2,000	0	2,000	0	2,000	0
Distribution system	18,000	9,000	9,000	10,800	7,200	12,000	6,000
Totals	$24,600	$11,000	$13,600	$12,800	$11,800	$14,000	$10,600
Fixed costs:							
Depreciation[a]	$ 1,609	$ 800	$ 809	$ 920	$ 689	$ 1,000	$ 609
Interest[b]	984	440	544	512	472	560	424
Property taxes[c]	172	77	95	90	82	98	74
Totals	$ 2,765	$ 1,287	$ 1,448	$ 1,522	$ 1,243	$ 1,658	$ 1,107
Operating costs:							
Fuel and power	$ 725	$ 362	$ 363	$ 445	$ 280	$ 483	$ 242
Repairs[d]	450	245	205	286	164	313	137
Labor	280	280	0	280	0	280	0
Totals	$ 1,455	$ 887	$ 568	$ 1,011	$ 444	$ 1,076	$ 379
Total annual inputs	$ 4,220	$ 2,174	$ 2,016	$ 2,533	$ 1,687	$ 2,734	$ 1,486
Percent each	100	51.5	48.5	60.0	40.0	64.8	35.2

a/ Based on the following assumed lengths of life: Water source -- 50 years; Pump -- 15 years; Motor -- 10 years; and Distribution System -- 15 years.

b/ Based on 4 percent of initial investment

c/ Based on 0.7 percent of initial investment

d/ Based on 2 percent of investments other than water source

A comparison of Table 1 with Table 2 shows clearly that the arrangements under the two-fifths rent-share leases were not equitable. Data in Table 1 indicate that tenants paying a two-fifths rent share were actually incurring about three-fourths of the total costs rather than the three-fifths share dictated by division of output. It should be noted that there is no single prescribed way of achieving a desired balance of inputs and returns. For example, the one-half rent-share leases proved quite equitable on the average (Table 1), but they differed from the model (Table 2) in that the landlords provided a larger share of the investment in the distribution system and a smaller share of the fuel and power cost. These variations should prove acceptable if the incentive conditions do not cause a conflict in achievement of objectives of the two parties. For example, where a landlord contributes more capital and less operating expense, his input is largely in fixed costs. The tenant's input is largely in variable costs. Therefore, the landlord would want to add water up to the point of no further yield increase. The tenant would want to add water only up to the point where his share of any added yield would cover his added cost. By sharing variable costs in the same way as the crops are shared both parties will have the same incentive toward added water use.

VIII. APPLICATION OF FINDINGS TO WATER RESOURCE PROBLEMS

The results of the research conducted under this project should serve to improve the base of information upon which farm-level decisions are made regarding irrigation of crops in Illinois. This will hopefully result in more rational decisions regarding use of the water resource in agriculture. The principal empirical findings have been distributed to farmers and agricultural leaders in Illinois. The results of the survey (Chapter II) were published in Illinois Research which has a circulation of 12,000 principally among persons having an interest in a wide range of developments in agricultural research. The results of the analyses of chapters III, IV, and V have been disseminated in Illinois Agricultural Economics, which is distributed to farm advisers, vocational agriculture teachers, farmers, persons in agricultural businesses, and also professional agricultural economists. The information on farm leasing provisions has been distributed in a letter, Farm Management Facts and Opinions, which is mailed to about 13,000 persons, principally in the Corn Belt. Articles in this letter are frequently reprinted in the farm press.

In addition to the empirical results, the comparison of various analytical approaches gives insight into the strengths and weaknesses of different research methods. These findings should prove of value to other researchers investigating the economic aspects of irrigation. The results strongly indicate the need for well-designed experiments which estimate the effect on crop yield of supplemental irrigation and accompanying crop production practices. These experiments should, ideally, provide for a sufficiently high level of water application to ascertain the economically optimal levels of application. Reliable estimates of the important interaction effects between accompanying production practices and levels of water application by periods are crucial.

IX. PUBLICATIONS RESULTING FROM PROJECT

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6. Papst, W. A. A Linear Programming Analysis of Irrigation Farming in Mason County, Illinois. Unpublished M.S. Thesis, University of Illinois. 1970.
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8. Reiss, F. J. Sharing Supplemental Irrigation Costs on Rented Land. Farm Management Facts and Opinions. FM No. 68-9. Department of Agricultural Economics, University of Illinois, June 10, 1968.