

EFFICIENT USE OF WATER FOR IRRIGATION IN THE UPPER MIDWEST

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Final Report Project B-120-ILL
WRC Research Report 176

Water Resources Center
University of Illinois at Urbana-Champaign
208 N. Romine Street
Urbana, IL 61801

April 1983

The work on which this report is based was supported in part by funds provided by the U.S. Department of the Interior as authorized under the Water Resources Research and Development Act of 1978, under agreement Number 14-34-0001-9113.

ABSTRACT

The objectives of this multidisciplinary interinstitutional regional study on the efficient use of water for irrigation in the upper Midwest were: (1) to determine parameters needed for existing or improved models of crop response; (2) to relate yield response to costs and revenues by assessing the water demand for irrigation; and (3) to study the demand for irrigation, present and projected, and its availability as related to public allocation decisions.

From this series of studies it was concluded that: (1) There are many areas of the Midwest with sufficient groundwater and surface water resources to support the development of irrigation. (2) Soil moisture models indicate that only moderate yield response to irrigation can be expected on high moisture soils; on lighter soils and claypan soils, yield response is significant, even in regions with relatively high precipitation. (3) Irrigation and drainage on claypan soils can dramatically increase corn yields. (4) It appears economically worthwhile for the individual farmer operating on moderate soils or on claypan soils to evaluate capital investments in irrigation along with other capital investments. (5) Increases in yields and persistence of alfalfa due to irrigation appear to be insignificant when compared to conventional management practices; further research is needed. A potential, however, appears to exist for improving adaptation of alfalfa varieties to soil water deficits.

KEYWORDS: Alfalfa, Corn, Soybeans, Irrigation, Midwest water resources, Groundwater, Surface water, Soil moisture, Soil moisture models, Claypan soils, Drainage, Economic models, Water use

EFFICIENT USE OF WATER FOR IRRIGATION IN THE UPPER MIDWEST. Water Resources Center, University of Illinois at Urbana-Champaign. April 1983.

G.E. Stout, P.N. Walker, W.D. Goetsch, M.D. Thorne, E.C. Benham, T.A. Austin, J. Golchin, Z. Shahvar, C.E. Anderson, H.P. Jackson, R.H. Shaw, O. Arjmand, W.L. Miller, R.L. Clouser, P. Erhabor, J. Sobek, V.R. Eidman, P.N. Wilson, and C.C. Sheaffer.

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I. INTRODUCTION

PROJECT BACKGROUND

In August 1977, directors of water research institutes or their representatives from Indiana, Iowa, Illinois, Minnesota, and Wisconsin met to make preliminary plans toward the development of a regional project to evaluate the efficient use of water for irrigation in the upper Midwest. It was agreed that there was an urgent need for such a regional project because of the rapid expansion of irrigation in the Midwest and the absence of information on the techniques and impacts of irrigation in the region. To conduct this research as efficiently and as quickly as possible, a regional approach was proposed. Each state institute agreed to present its ideas in October to the director of the Illinois Water Resources Center. Proposals were received from four of the five states and those proposals were integrated into one regional proposal and submitted to the Office of Water Research and Technology.

There were several broad objectives that the regional project would address. The project would:

1. Determine parameters needed for existing or improved models of crop yield response to water.
2. Relate yield response to costs and revenues by assessing the water demand for irrigation.
3. Study the demand for irrigation, present and projected, and water availability as related to public allocation decisions.

THE PROBLEM AND RESEARCH NEEDS

Increased variability of weather conditions during the past few years has increased the economic opportunity to include irrigation systems in agricultural operations in the upper Midwest. The increase in weather variability

has been accompanied by a period of rising land prices and operating costs. The higher risk resulting from these changing conditions has encouraged the rapid adoption of irrigation systems by farmers in the region. Social and economic research has not been undertaken to assess these changing conditions. It is essential to provide research information for farm managers and public officials responsible for the prudent development and use of water supplies.

This problem has been identified as a high priority research issue by water experts and political leaders. The Department of the Interior's Office of Water Research and Technology (OWRT) referred to the research needed on "increased supplemental irrigation in the more humid parts of the country to compensate for the decreased crop production that might be experienced in the West because of dwindling water supplies" under perceived research needs in reference to water conservation. OWRT also indicated that research needs include "examination of the consequences of supplemental irrigation to the economy in relation to food reliability and short- and long-term groundwater and soil effects" under drought research needs. These OWRT priorities were developed by the 1979 Title I Water Research Programs from several different sources.

Technological advances of the last century have made many of man's activities seemingly immune to the vagaries of weather and climate. A severe weather event--a drought, a flood, or an immobilizing blizzard--provides an occasional reminder, however, that our protection from the elements is far from total. Although few in our largely urban society realize it, climate and weather affect man daily through the one commodity that he cannot do without--food. This point may be brought forcibly home periodically because of severe and widespread droughts somewhere in the world. However, nonsevere conditions, perhaps only slightly less than optimum weather conditions, are

reflected in our urbanized society in smaller food supplies and larger food bills because of reduced crop productivity. Weather is now becoming recognized as the limiting factor against further major gains in national agricultural production.

With the continuing increase in the world's population there is an ever-growing need for an increase in both food supplies and the stability of those food supplies. Among the main conclusions drawn by a special study group of the National Research Council were:

1. Fluctuation in weather and climate is a major cause of season-to-season variation in food production.
2. Variability in climate over periods of a season to a few years is more important than long-term trends because it is more difficult for agriculture to respond to short-term changes.

Crop production is sensitive to many climatic factors, but for most food crops growing-season precipitation is the most important. In many parts of the world with good soils, a limitation on agriculture is the availability of water. In many of these areas greater overall productivity, either of existing crops or through multiple cropping, would be possible if there were a more adequate and reliable water supply. Even small increases in water could provide significant benefits to these areas, particularly if the increases were more consistent. Thus, benefits could be realized not only in periods of climatic stress but also in times of normal or near normal precipitation if the precipitation could be increased (Huff and Changnon, 1972).

Irrigation to increase the crop water has the potential for providing significant benefits to agriculture by:

1. Increasing yields in most years since the precipitation is less than that needed for optimum production.

2. Decreasing the year-to-year variations in production.
3. Providing temporary relief from the stresses of drought.

The first two contribute the greatest benefits because of the overall increase in, and greater stability of, food supply. It is doubtful that irrigation in the upper Midwest can provide major relief in severe and extensive (time and area) droughts, which are usually associated with periodic changes in major weather patterns, unless major water storage developments were constructed. However, past studies and those in progress indicate that, in the upper Midwest, irrigation may alleviate the stresses of moderate droughts and possibly may also provide some local easing of conditions in major droughts.

Indications of a changing, more variable climate and the continued seriousness of the world food situation have awakened concern over the impact of weather in the Midwest, the nation's most important agricultural area. Blessed with generally good soils, this region also has a subhumid climate that in most years provides adequate, although possibly not always optimal, moisture for food crop production. The continental climate is also quite variable so that season-to-season rainfall can vary considerably and, with it, crop yields. Interest has heightened in irrigation as a potential means to increase midwestern yields. Recent studies comparing crop yields to rainfall have shown that a relatively small (10 to 20%) increase in growing season rainfall could produce 5 to 10% increases in midwestern crop yields. Moreover, management of the crop water supply would help stabilize production variability.

Moderate to severe summer droughts that developed in the central portions of the Corn Belt in 1974, 1975, and 1976 led local farm units in Iowa, Minnesota, Indiana, and Illinois to increase irrigated acreage substantially. Despite the current economic uncertainties, agricultural groups have time and again perceived potential benefits as being large relative to the cost, and have taken the risk of investing in irrigation systems. Irrigation in the

upper Midwest expanded in 1977 beyond expectations. However, high interest rates, lower water tables in the Great Plains, and low commodity prices in the early eighties have reduced the growth of irrigation considerably in the Midwest.

THE STUDIES SUMMARIZED

The following sections summarize the studies of irrigation in the upper Midwest carried out by the University of Iowa, University of Illinois, Purdue University, and the University of Minnesota. These sections are only summaries, compiled with the intention of providing an overview to the entire project. For detailed information on any of the topics, the reader should contact the particular researcher or the report noted at the beginning of each section or listed in the section Publications Resulting from Project Research.

II. AVAILABILITY OF WATER FOR IRRIGATION IN THE UPPER MIDWEST*

The question of water availability for irrigation in the upper midwest states is central to the continued expansion of irrigation in this region. Even though this region is considered to be largely a water surplus region, there are limits to the volume of water that can be used for beneficial uses. The purpose of this chapter is to present the alternative water supplies for irrigation and to discuss the subregions where adequate water supplies could be available for expansion of irrigation development. This chapter will not discuss the water law and water allocation systems used by the various states. These laws, rules, and regulations can override the physical system analysis described in this chapter.

IRRIGATION USE

Unlike water use by municipalities, the use of water for irrigation is considered a consumptive use since most of the water is dissipated by evaporation from the soil and evapotranspiration by the plants. Large withdrawal rates are also needed for irrigation. In 1975 irrigation had the largest withdrawal (158,743 mgd or 6955 m³/sec) and the largest consumption (86,391 mgd or 3785 m³/sec) of water in the United States of all function uses (U.S. Water Resources Council, 1978). Total water withdrawals for irrigation in the United States are projected to decrease by the year 2000, but the total consumption is projected to increase. This is due to expected improved efficiencies in irrigator water use. Much of the new irrigation development in the upper Midwest uses sprinkler irrigation with little or no irrigation

*This section summarizes the research of T. A. Austin; and J. Golchin; reported in Chapter 2 of Efficient Use of Water for Irrigation in The Upper Midwest, ISWRI-117, Iowa State University, Ames, IA, June 1981.

return flows. Thus, a high percentage of the water withdrawn for irrigation will be consumed for irrigation in this region. According to the U.S. Geological Survey (Murray and Reeves, 1972), a total of 221,000 ac.ft. ($272.5 \times 10^6 \text{m}^3$) of water was withdrawn for irrigation in the upper Midwest (Minnesota, Iowa, Wisconsin, Illinois, and Indiana) in 1970, with almost 100 percent being consumed or lost during conveyance. About 77 percent of the water withdrawals were from groundwater sources. Since much of the irrigation in this region is "supplemental," in that it may not be necessary every year, exact data on water withdrawals for irrigation in any year are difficult to obtain.

Expansion in the number of irrigated acres in the upper Midwest has been dramatic in the recent years. Table 2.1 shows the estimated irrigated acreage and the irrigated acreages using sprinklers for the years 1966 to 1979. In many states a major expansion in irrigated acres has occurred since 1975. For example, in Iowa the estimated irrigated acres expanded 231 percent for 1975 to 1979.

In the six states included in this study, about 1.25 million acres (5060 km^2) are estimated to have been under irrigation in 1977 (Table 2.2). About 55 percent of this land was irrigated by sprinkler irrigation from groundwater. Average application rates varied from 5.4 inches/year (137 mm/yr) in Wisconsin to 10.2 inches/year (260 mm/yr) in Indiana.

GROUNDWATER RESOURCES

Groundwater resources have always been one of the most important water supplies in this region. As the demand for quality water increases, more attention will need to be directed toward groundwater management. Effective management of groundwater requires knowledge of both its availability and quality, which is dependent mostly on the structure of the geological formations in the region and the material composition of these formations.

Table 2.1. GROWTH OF IRRIGATED AREAS IN THE UPPER MIDWEST

Acresage Irrigated

Sprinkler Irrigation

Year	IL	IN	IA	MN	MO	WI	IL	IN	IA	MN	MO	WI
1966	--	--	--	24,000	108,489	--	--	--	--	24,000	32,763	--
1967	30,000	30,400	91,000	25,000	99,118	109,750	27,500	22,700	40,000	25,000	27,171	106,800
1968	32,000	34,400	93,000	--	145,305	110,000	30,000	26,000	41,000	--	33,166	106,600
1969	34,000	35,100	95,000	35,000	168,800	110,000	32,500	27,000	42,000	35,000	39,200	106,500
1970	36,000	36,200	80,000	45,000	172,054	120,000	34,500	28,000	38,000	44,379	40,080	116,500
1971	37,000	36,200	65,000	58,000	196,339	146,000	35,750	28,000	34,000	55,466	46,158	139,660
1972	38,000	37,000	50,000	68,000	--	--	37,000	28,750	30,000	64,338	--	--
1973	37,100	37,350	45,000	92,000	--	--	37,000	29,800	30,000	86,166	--	--
1974	50,000	38,330	60,000	118,000	216,339	162,560	49,000	30,080	30,000	111,233	50,000	166,485
1975	50,000	43,330	95,000	183,000	216,339	172,000	49,000	35,080	55,000	174,094	50,000	165,200
1976	53,000	47,720	131,500	230,000	242,325	180,810	52,000	39,470	91,500	221,521	85,300	173,810
1977	68,000	58,250	165,000	397,500	266,558	253,000	67,000	49,900	130,000	387,000	91,800	251,200
1978	110,000	71,000	180,000	433,500	266,588	253,000	109,000	65,000	145,000	433,000	91,800	253,000
1979	125,000	87,000	220,000	450,500	353,000	253,000	124,000	81,000	195,000	450,000	142,760	253,000

After Irrigation Journal, 1976 to 1979

Table 2.2 Estimated Irrigated Acres for Upper Midwest Regions by Method of Application and Source of Water (After Irrigation Journal, 1979)

State	Water Application in/yr	Method of Application	Irrigated Acres	
			Surface Water	Groundwater
Illinois	8.2	Sprinkler	2,000	65,000
		Flood	200	800
Indiana	10.2	Sprinkler	13,000	38,000
		Subsurface	5,000	-
Iowa	7.0	Sprinkler	40,000	90,000
		Flood	8,000	27,000
Minnesota	9.5	Sprinkler	96,750	290,250
Missouri	6.0	Sprinkler	90,000	52,000
		Flood	12,000	175,000
		Drip	100	100
Wisconsin	5.4	Sprinkler	92,515	157,000
		Flood	-	1,805
		Drip	-	360
Regional Totals		Sprinkler	334,265	692,250
		Flood	20,200	204,605
		Drip	100	460
		Subsurface	5,000	-
			<hr/>	<hr/>
			359,565	897,315

An aquifer is a geological formation that contains and transmits sufficient quantities of water for economical development. Aquifers can be described and classified into those that are unconsolidated and those that are consolidated or bedrocks.

Groundwater in the upper midwest region occurs in a variety of both unconsolidated and bedrock aquifers. The most significant unconsolidated aquifers are alluvial deposits associated with the current river system, glacial outwash sand and gravel deposits, and glacial drift. Some bedrock formations of limestone, dolomite, and sandstone are usable aquifers in the region. Figure 2.1 is a map of the upper midwest region showing the locations of the major aquifers. The capability of individual aquifers to yield sufficient quantity of water with good quality is somewhat variable from place to place in the region. Thus, the groundwater availability from a particular aquifer in a particular spot cannot be totally regionalized. Test drilling and pumping at individual sites will be required to assess accurate groundwater quantities and withdrawal rates.

Glacial Deposits

The glaciated area in the region is part of the central glaciated region that exists between the northern Rocky Mountains on the west and the Appalachian Mountains on the east, and between the Canadian border on the north and unglaciated central region on the south (Thomas, 1952). Within these boundaries, the only area in the study region not included is the small driftless area of southwestern Wisconsin, southeastern Minnesota and the extreme northeastern Iowa. Glacial sand and gravel deposits are important aquifers in the study region, but in general do not yield sufficient quantities of water for large-scale irrigation development.

Alluvial Deposits

Alluvial deposits of substantial width and thickness and moderate-to-high permeability are found only along the major streams and rivers in the study area. The most important within the region are those along the lower Missouri River and its associated tributaries in Iowa and Missouri, the upper Mississippi River and the stretch of the Ohio River between Indiana and Kentucky (Meinzer, 1940). The Missouri and Ohio Rivers run approximately along the boundary between the glaciated and unglaciated central regions. The alluvium deposits along these rivers are good aquifers nearly everywhere along the flood plains.

Alluvial deposits along the major rivers are often well graded coarse sands and gravels ranging in thickness up to 100 feet (30.5 m) or more. These formations are often easily recharged from the rivers. These alluvial aquifers appear to have the potential water supply to permit expansion of irrigation along the flood plains of the major rivers. Cost may prevent the development of alluvial deposits for irrigation of upland sites because of the added pumping and pipeline expenses.

Bedrock Aquifers

Consolidated rock formations can, under certain conditions, store and transmit sufficient quantities of water to be classified as an aquifer. Sedimentary rock units--such as limestone, sandstone and dolomites--are most frequently aquifers.

Figure 2.2 shows the bedrock units, by geological age groups, that exist immediately below the surficial cover. The arrows on Figure 2.2 indicate the direction of the slope (dip) on the units. The legend shows the geological age groups arranged from the most recent age rocks (Quaternary) to the oldest age rocks (lower Precambrian). At any location, the bedrock units of earlier

age than those shown in Figure 2.2 either have been eroded away or never existed. For example, in central Illinois the latest age rock units are of Pennsylvanian age. Quaternary, Eocene, and Cretaceous rocks do not exist in central Illinois. However, all rock units older than Pennsylvanian age should be found in central Illinois.

In the region as a whole, the limestone aquifers are the most productive single type of bedrock formation, though the sandstone of the driftless area is locally capable of high yields to individual wells.

Cavernous limestone is a somewhat uncertain aquifer. A well that penetrates a cavernous zone may have a very large yield while one a short distance away, a well may yield little or nothing. Furthermore, a large yield may not indicate a large storage capacity in the rock. Geological studies of carbonate rocks indicate that newly formed carbonate rock has little or no capacity to store or transmit water (Meinzer, 1940; U.N., 1976). Some units have been transformed into important aquifers, however, as a result of recrystallization (i.e., the development of a system of fractures in the rock) and through solution of the rock by weak acids. Limestone aquifers generally have rather small storage capacity but great capacities to transmit water. Success in obtaining a water supply from a limestone aquifer ordinarily depends on whether the well intersects one or more solution channels or open fractures. Dolomite, also a carbonate rock, may have a moderately high capacity to store water and to yield it to wells.

Metamorphic and igneous rocks can be found in the northern and northwestern part of the region (Figure 2.2). Few of these rocks (Precambrian age) can store or transmit large quantities of water. Most of these rocks are fractured to some degree, however, and in some places may yield enough water for domestic needs.

Figure 2.1 shows the location of the major sandstone and carbonate aquifers in the study region. Many of these rock units are capable of producing sufficient water for irrigation development.

Water Quality

The importance of an aquifer is usually determined by its yield, storage capability, and the quality of water within the aquifer. One aquifer may have a large storage capacity and high transmitting ability but be of such poor water quality that it cannot be used by some users.

The water quality criteria necessary for irrigation water are not the same as those for drinking water. The most important parameters in irrigation water quality are total dissolved solids concentration, the proportion of sodium in relation to other cations, and the presence of toxic ions such as boron. Water with total dissolved solids in excess of 1500 to 2000 mg/l should be carefully evaluated for use in irrigation. The exchangeable sodium in the irrigation must be balanced with the other exchangeable cations, primarily calcium, magnesium, and potassium, in order to prevent the buildup of sodium in the root zone to potential toxic levels.

Conclusions

Considering both groundwater availability and groundwater quality in the upper Midwest, the most probable expansion of irrigated lands would be on lands near alluvial aquifers associated with the major rivers in the region or in areas where bedrock aquifers are near the surface. These areas could include the Missouri, Mississippi, and Ohio River flood plains and associated tributaries. Bedrock formations could be used in southeastern Minnesota, northeastern Iowa, north central Illinois, and eastern Indiana. Irrigation

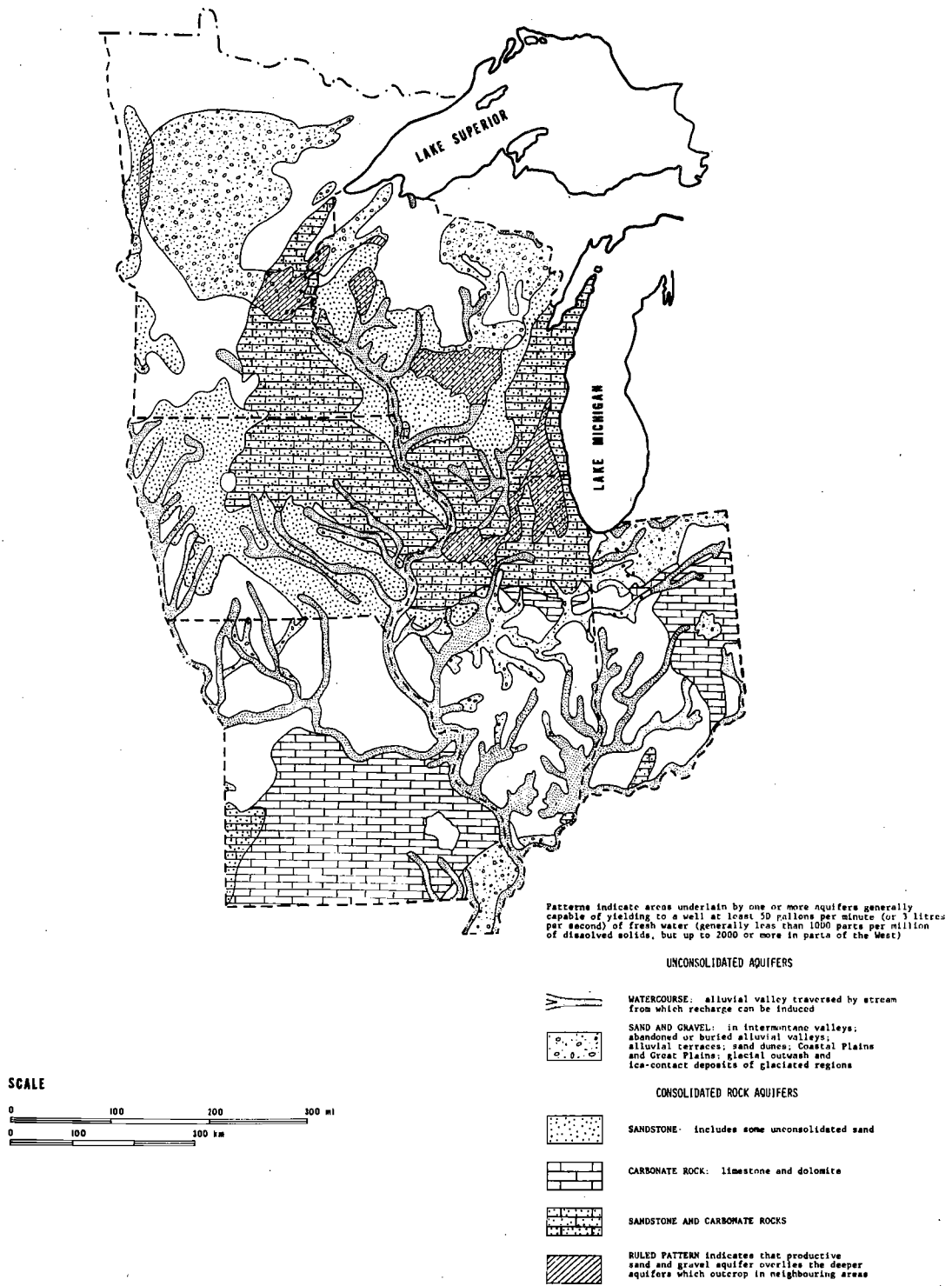


Fig. 2.1. Upper midwest major aquifers.

Source: Austin et al. 1982

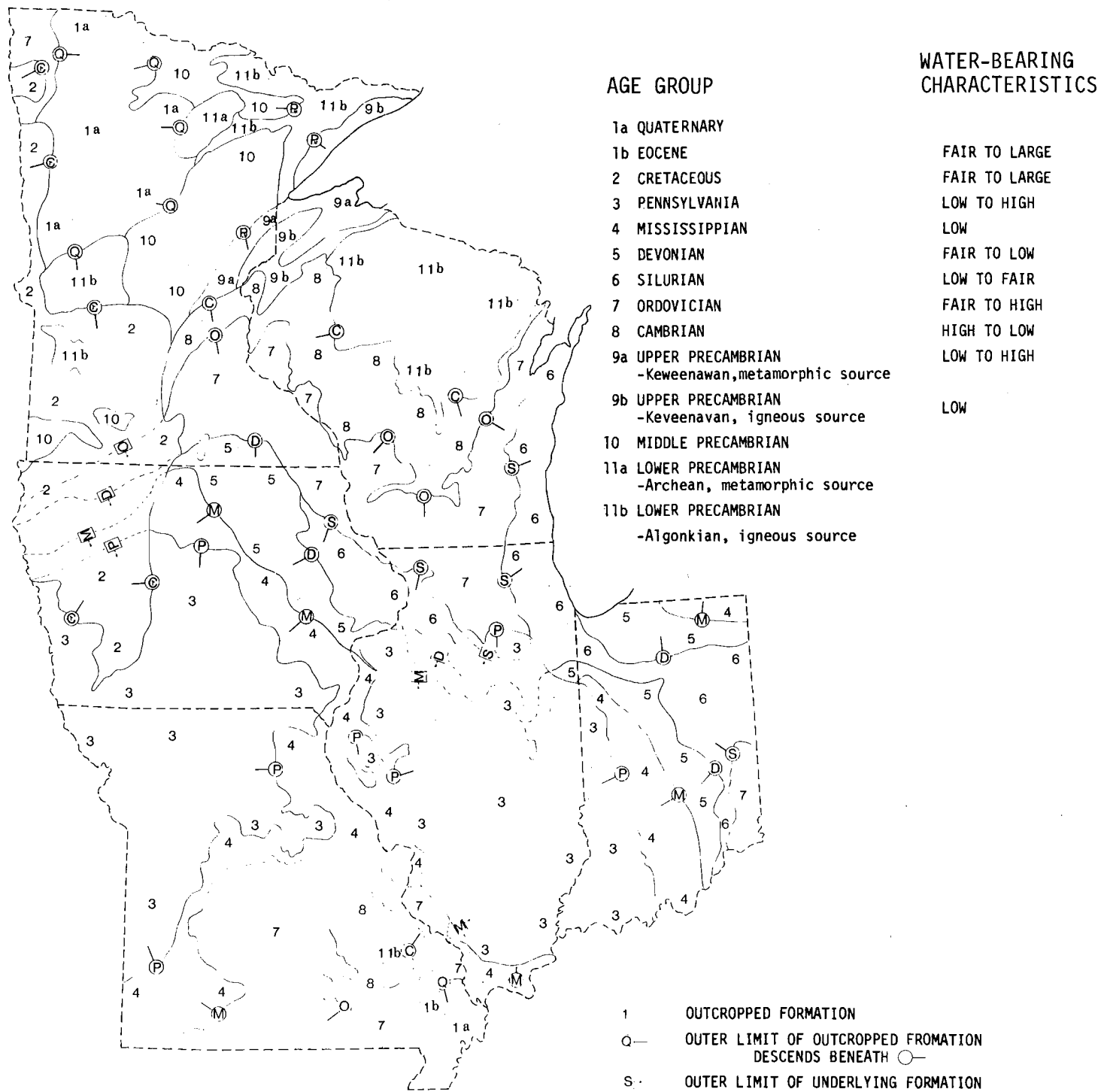


Fig. 2.2. Geologic and hydrogeologic units of upper Midwest.

Source: Austin et al. 1982

from the Dakota formation in southwestern Minnesota and northwestern Iowa may be possible.

Northwestern Missouri, southwestern Iowa, and northern and northwestern Minnesota have little potential for increased irrigation from the bedrock formations.

Individual states may have groundwater laws that limit the amount of irrigation from these formations. These constraints have not been included in the above analysis. Persons interested in irrigation from these formations should contact their state geological survey and the state agency responsible for management of these aquifers.

SURFACE WATER RESOURCES IN THE MIDWEST

Introduction

Most of the study region is considered a humid region. Average annual precipitation varies from just under 20 inches/year (420 mm/yr) in extreme northwestern Minnesota to more than 40 inches/year (840 mm/yr) in southern Missouri, Illinois, and Indiana. The average annual runoff for the upper midwest study region varies from less than 1 inch/year (20 mm/yr) to more than 15 inches/year (320 mm/yr). The amount of runoff from a region is a function of its precipitation, land cover, soil type, slope, and other factors.

The amount of moisture required for good corn and soybean production varies from year to year according to many climatological factors, but on the average about 20 to 25 inches/year (420 to 530 mm/year) is required. In the northwestern portion of the study area (northwestern Iowa and western Minnesota), sufficient moisture is usually not available. In the southern one-half of the region, annual precipitation is sufficient to supply crop

needs, but the timing of the precipitation may not meet optimal crop requirements. In southern Illinois and Indiana, the soils are shallow with little moisture holding capacity; consequently, irrigation may be necessary in these areas even though annual precipitation is quite high. Much of the irrigation in the upper midwest region will "supplement" the annual precipitation in order to relieve short-term crop moisture stress during the growing season and provide needed moisture during periodic droughts. Annual irrigation demands may vary from zero up to 15 inches/year (320 mm/year), depending on precipitation, soil type and other factors.

Streams, Rivers, and Lakes

Direct diversion of water from streams, rivers, and lakes for irrigation is possible along the major rivers and associated tributaries, especially in the southern one-third of the region. Care must be taken to evaluate the availability of water from these rivers during extended drought periods. In most of the areas where direct diversion is possible, shallow alluvial aquifers are also available. The location of the land to be irrigated in relation to the stream or river, and the cost and reliability of the surface flows will determine which source is most economical.

Storage

Ponds and reservoirs can be used to provide water for irrigation. A pond can be used to store water during high runoff times for later irrigation use. The volume of storage needed for irrigation is a function of the variability of runoff in the area, the amount of land irrigated, sediment trapped in the pond, and evaporation from the pond.

One possible solution which will provide an adequate volume of storage for short- or long-term droughts is to construct a pond that collects all the

runoff from a given area. This water can then be used to irrigate the crop later in the season.

A preliminary evaluation of the volume of on-site pond storage needed during a critical three-year drought period in order to provide varying amounts of irrigation water was conducted as part of this project. This evaluation does not include an analysis of the short-term storage required because of seasonal variations in rainfall, but it does account for expected reductions in precipitation and runoff, and increases in pond evaporation during a critical three-year drought period. No estimate of sediment storage has been included. A simulation model was used to analyze the on-site storage required for 2 inches/year (42 mm/yr), 4 inches/year (84 mm/yr), and 6 inches/year (126 mm/yr) irrigation application.

Results indicate that on-site storage of water in small ponds for irrigation is possible, but in the northern two-thirds of the study area, substantial land must be set aside for the pond. Local topography and sediment yields must be carefully evaluated in assessing the feasibility of on-site storage.

Conclusions

Adequate surface water resources are available for irrigation development, especially in the southern one-half of the region. However, carryover storage of water both for short-term variations within a year and long-term droughts will probably be needed. Direct diversion will only be possible from the major rivers of the region and their associated tributaries. On-site storage of water for irrigation can be done, but it requires significant land and the proper topographic conditions. Off stream impoundments, where water can be diverted from surface streams during high flows, can also be used to provide water storage.

III. IRRIGATION WATER NEEDS -- FREQUENCY OF SOIL MOISTURE SHORTAGES*

In an area such as Iowa where corn is grown under a high level of management and other factors such as fertility are not limiting, the amount of moisture available to the corn plant may be the limiting factor determining grain yield. Periods of drought are common in western Iowa and supplemental irrigation may provide the method for reducing or eliminating moisture stress as an important influencing factor in corn yield.

OBJECTIVES AND PROCEDURES

The general objective of this study was to define probability of soil moisture shortage on selected soils and for selected crops in the upper Midwest. A water balance model (Anderson, 1975) was used to predict soil moisture shortage at Doon watershed located in Lyon county, Iowa. The soils were Moody silt-loam, 2-5% slope, and well drained. The North watershed used in the study was under corn and contour-surface planted.

The water balance model was calibrated and evaluated by using the available measured surface runoff at North watershed (DeBoer and Johnson, unpublished data) and reported soil moisture data by Shaw, et al. (1972). The model predicted surface runoff reasonably close to the measured values. No significant difference was observed between the top five-foot soil moisture reported by Shaw and those predicted by the model for May, June and July; however, for August and September, models predicted lower soil moisture values

*This section summarizes the research of Z. Shahvar; C.E. Anderson; and H.P. Johnson; reported in Chapter 3 of Efficient Use of Water for Irrigation in the Upper Midwest, ISWRR1-117, Iowa State University, Ames, IA, June 1981.

than those reported by Shaw.

Twenty-one years of the available weather data (1958 - 1978) at the watershed then were used in the model to determine the probability of moisture shortage, providing that moisture shortage occurs on days when total soil moisture in the top five feet is less than a predetermined percent of the available soil moisture value. The length of the stress period was determined to be a function of the initial soil moisture and growing season rainfall for a given year. Two moisture level criteria were used in the program as requirements for scheduling irrigation:

1. Water was applied when the total soil moisture in the top five feet fell to 50% or less available moisture (FC-WP) for the top five feet. This will be referred to as the "50% criterion."
2. Water was applied when the total soil moisture in the top five feet fell to 70% or less available moisture value for the top five feet. This will be referred to as the "70% criterion."

The criteria were compared in terms of both irrigation application frequency and the total inches of irrigation water application by running the program twice for each year while holding all of the parameters constant except the moisture level at irrigation. This comparison is illustrated in Figure 3.1 with the numerical values given in Table 3.1.

A comparison of the amount of water used for each criterion and a consideration of the beginning soil moisture and rainfall indicate that the largest difference is shown in 1959 when 12.0 inches of water were used for the 70% criterion and 4.0 inches of water were used under the 50% criterion. The reason for this difference is that the level of the beginning soil moisture

(11.0 inches) for this year was below the 70% criterion (11.38 inches) and above the 50% criterion (10.09 inches). Preseason irrigation was required. A similar condition resulted in a late irrigation under the 70% criterion (August 31) which was not required by the 50% criterion.

For ten of the twenty-one years, two irrigations were used under the 70% criterion and one under the 50% criterion. In these years the combination of the beginning soil moisture and rainfall were such that one irrigation would hold the moisture level in the top five feet above the 50% criterion for the season, but another irrigation was required to keep it above the 70% criterion.

Irrigation schedules were also compared where different depths of water were applied per irrigation. Irrigation water was applied under the 70% criteria using the following application depths and time periods:

1. Four inches of water were applied in twenty hours.
2. Two inches of water were applied in twelve hours.
3. One inch of water was applied in six hours.

The results of these analyses are shown in Figure 3.2.

From the results of this comparison it can be concluded that applying irrigation water more frequently in smaller amounts will reduce the total amount of water required to hold the top five feet at the 70% criterion (11.38 inches).

The application frequency of the amount of irrigation water applied per growing season was determined using the results of the twenty-one years in each irrigation schedule. Figure 3.3 illustrates the frequency distribution of irrigation application depth for the two different soil-moisture levels at irrigation time when a four-inch application was used. The graph shows that a four-inch depth of irrigation water was the most frequent depth for the

50% criterion (eleven out of twenty-one years) and eight inches under the 70% criterion (nine out of twenty-one years).

CONCLUSIONS

Irrigation was applied using 50% and 70% criterion, that is when 50% and 30% of the available soil moisture in the top five feet have been removed. Based on the results of the study, a depth of 4-inches of irrigation water was the most frequent depth for 50% criterion and a depth of 8-inches under 70% criterion when a rate of 4-inch per application was used. Using the 70% criterion, preseason irrigation is required sometimes, even with the high average annual precipitation in the upper Midwest.

The average irrigation water applied for the 21-year study period was 5.5 and 7.6 inches for the 50% and 70% criterion, respectively. However, as much as 12 inches per year was required for several years to meet the application criteria.

Table 3.1. Comparison of irrigation schedules for two stress levels and for three amounts of irrigation water applied.

Year	Growing Season Rainfall 4/1-9/31 (inches)	Irrigation Schedule											
		Four Inches of Water in 20 Hours at 50% Available Moisture			Four Inches of Water in 20 Hours at 70% Available Moisture			Two Inches of Water in 12 Hours at 70% Available Moisture			One Inch of Water in 6 Hours at 70% Available Moisture		
		Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)
1958	11.19	2	8	2	8	4	8	4	8	4	8	8	8
1959	24.62	1	4	3	12	4	4	4	8	4	8	6	6
1960	23.13	1	4	1	4	2	4	2	4	2	4	3	3
1961	21.33	1	4	2	8	3	8	3	6	3	6	6	6
1962	19.14	1	4	1	4	2	4	2	4	2	4	4	4
1963	14.72	2	8	2	8	4	8	4	8	4	8	7	7
1964	18.81	1	4	1	4	1	4	1	2	1	2	2	2
1965	28.18	1	4	2	8	3	8	3	6	3	6	5	5
1966	19.90	2	8	2	8	4	8	4	8	4	8	7	7
1967	15.93	2	8	3	12	5	10	5	10	5	10	9	9
1968	23.10	3	12	3	12	6	12	6	12	6	12	11	11
1969	18.35	1	4	2	8	3	8	3	6	3	6	5	5
1970	16.71	2	8	3	12	5	10	5	10	5	10	9	9
1971	15.87	2	8	2	8	4	8	4	8	4	8	7	7
1972	24.88	1	4	2	8	3	8	3	6	3	6	5	5
1973	21.83	1	4	1	4	2	4	2	4	2	4	2	2
1974	13.25	1	4	2	8	3	8	3	6	3	6	6	6
1975	20.30	1	4	1	4	2	4	2	4	2	4	4	4

Table 3.1. Continued.

Year	Growing Season Rainfall 4/1-9/31 (inches)	Irrigation Schedule											
		Four Inches of Water in 20 Hours at 50% Available Moisture			Four Inches of Water in 20 Hours at 70% Available Moisture			Two Inches of Water in 12 Hours at 70% Available Moisture			One Inch of Water in 6 Hours at 70% Available Moisture		
		Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)	Number of Times Water Applied	Total Water Used (inches)
1976	10.02	2	8	3	12	5	10	9	9	2	2	1	1
1977	23.96	0	0	1	4	1	2	2	2	2	2	2	2
1978	18.38	0	0	1	4	1	2	1	2	1	2	1	1

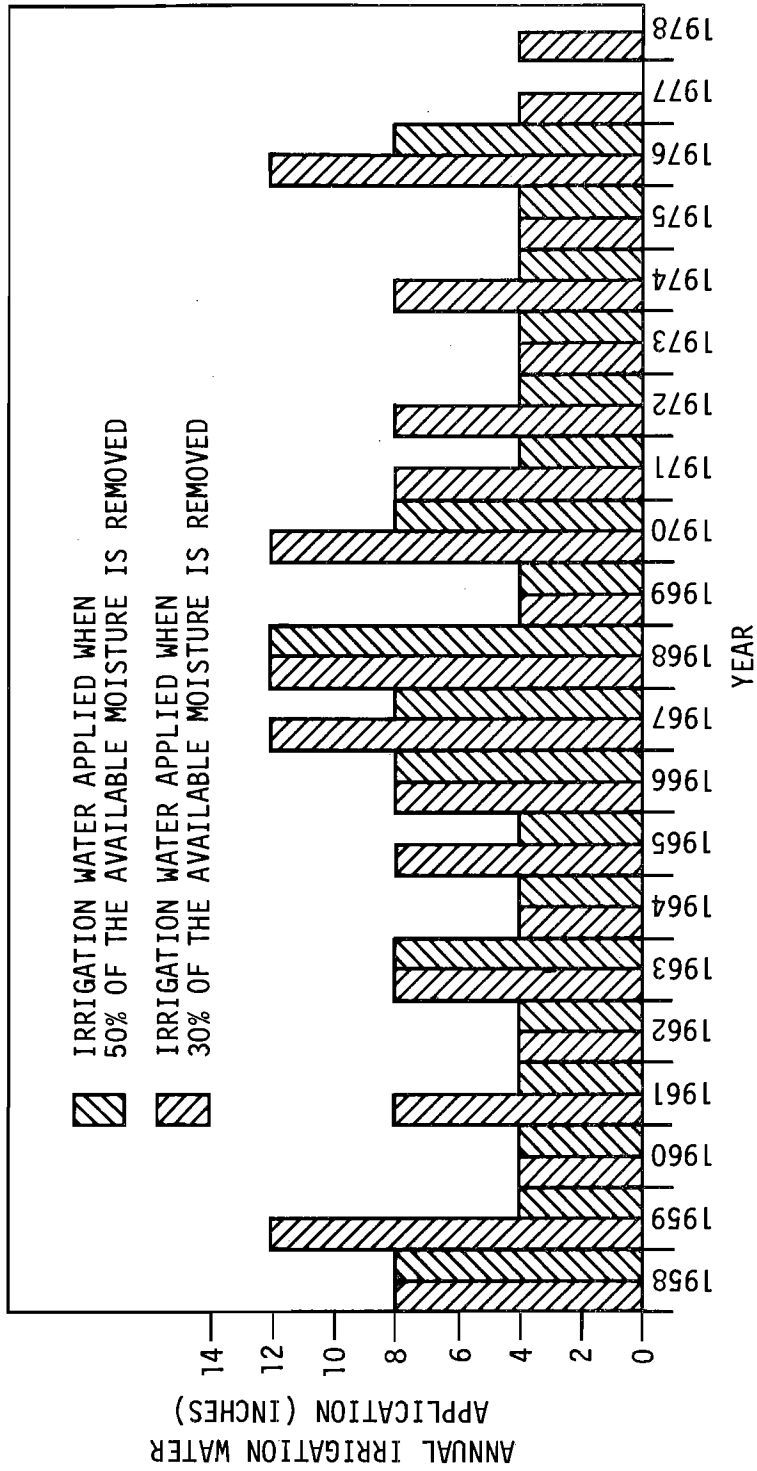


Figure 3.1. Comparison of the annual irrigation water used when irrigation water applied after 50% and 30% of the available moisture is removed from the top five feet (1958-1978).

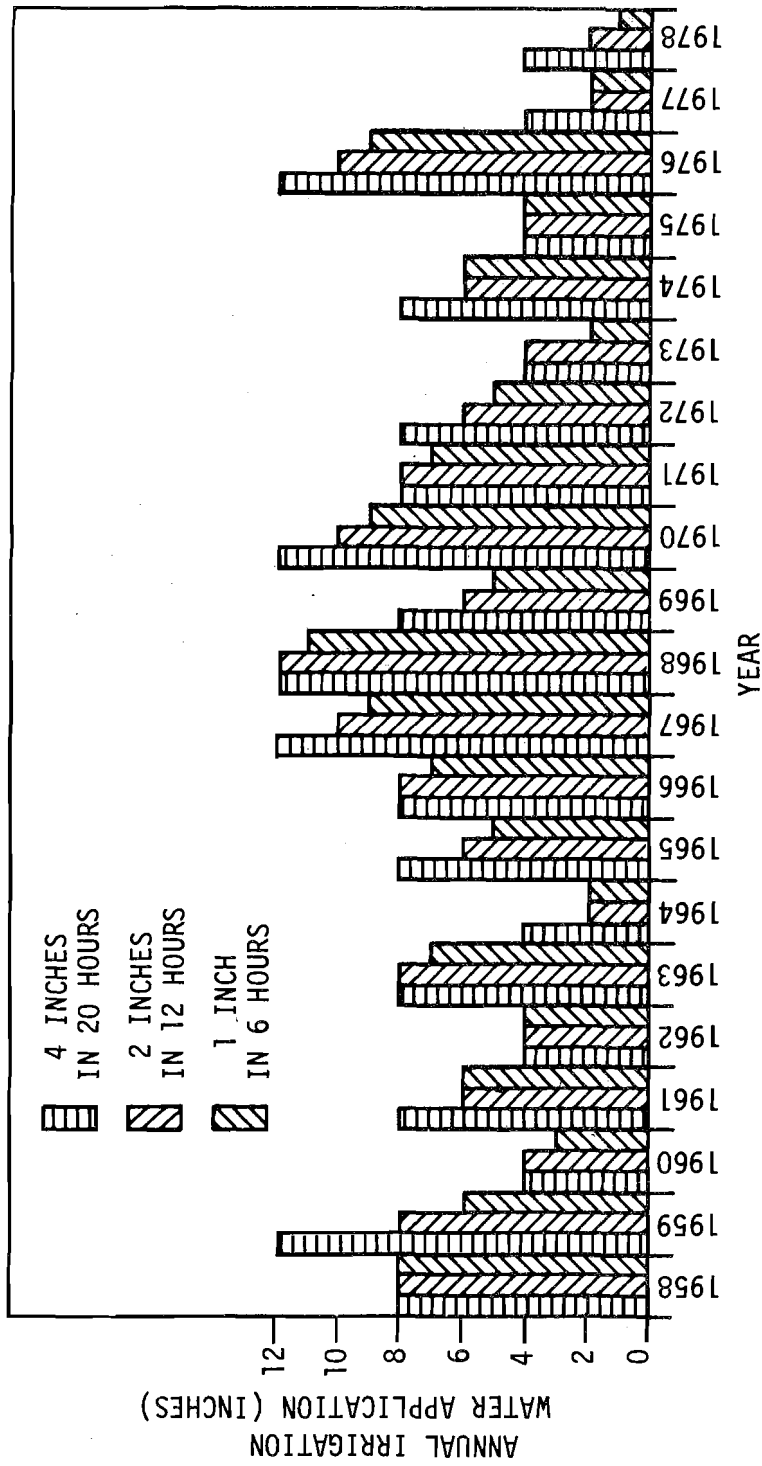


Figure 3.2. Comparison of the three methods of irrigation application in terms of the annual irrigation water used under each method at north Doon watershed (1958-1978).

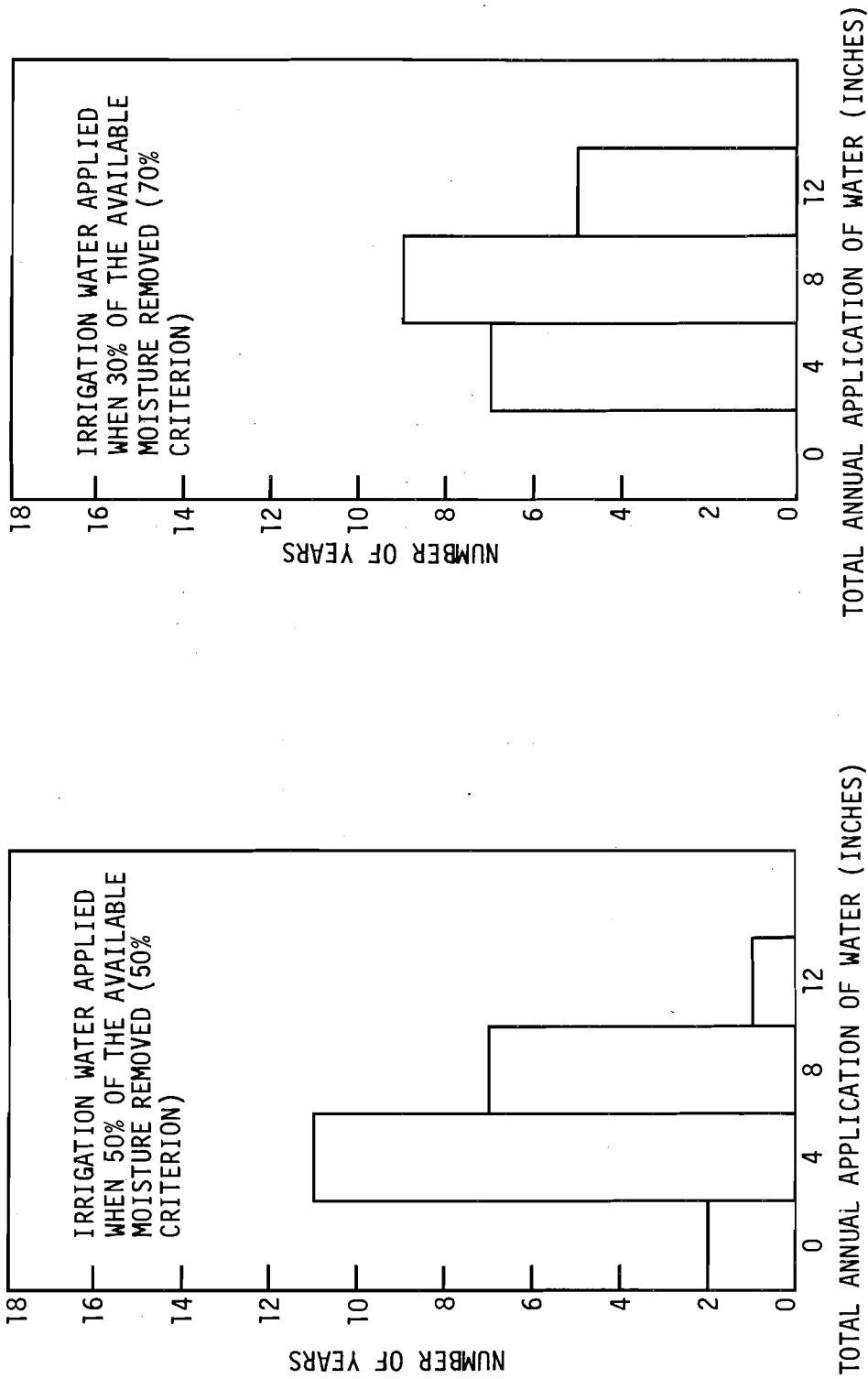


Figure 3.3. Frequency of annual irrigation water application for irrigation water applied when 50% and 30% of the available moisture has been removed at north Doon watershed (1958-1978).

IV. USE OF A SOIL-MOISTURE PROGRAM IN EVALUATING IRRIGATION POTENTIAL*

The objective of this part of the study was to evaluate the increases in corn yields expected due to irrigation using an existing corn yield/soil moisture program developed at Iowa State University.

A soil-moisture program has been in operation in Iowa for a number of years. Using a starting, measured soil moisture in the spring, with daily inputs of rainfall and pan evaporation and the proper soil moisture characteristics, soil moisture can be estimated under corn throughout the growing season. A moisture stress index calculated in conjunction with the soil moisture program is used to predict corn yields. By including an irrigation cycle in the program, the response to irrigation can be estimated. Different types of soils can be examined by changing the soil characteristics in the program.

PROCEDURES

The procedures used to calculate soil moisture and yield response to irrigation are based on a soil-moisture program (SOIL MOIST I) and a stress index.

The soil-moisture balance is calculated on the plant available water, i.e., the water between field capacity and the wilting point. The field capacity can only be determined accurately by field measurements. The wilting point is estimated by the 15-bar value determined in the laboratory. Gains in moisture are determined by subtracting runoff from precipitation. The amount

*This section summarizes the research of R.H. Shaw; and O. Arjmand; reported in Chapter 4 of Efficient Use of Water for Irrigation in the Upper Midwest, ISWRI-117, Iowa State University, Ames, IA, June 1981.

of runoff depends upon an antecedent precipitation index. The remaining water is added to the profile. Moisture is lost from the profile by evapotranspiration, and, in the original program, any water above field capacity was percolated out the bottom of the profile. When rainfall, or irrigation, occurs, water is added to the profile to bring the top layer (top 6 inches) to field capacity, then the second layer (6-12 inches) is brought to capacity, and so forth through the profile, until all layers considered are at the value set for field capacity. Any excess water is percolated out of the profile. The original soil moisture program was modified for use on a soil with slow internal drainage. The infiltration and redistribution aspects of SOIL MOIST I had to be modified as SOIL MOIST II to apply to a poorly drained soil.

A third soil moisture program, SOIL MOIST III, was written to represent more closely the situation that exists as a Cisne soil with a claypan at 24 inches.

A subroutine was developed to simulate irrigation, which was added to the soil-moisture program to determine the effects irrigation might have in reducing moisture stress in corn. This subroutine simulated irrigation of a point in a large corn field (approximately 160 acres). The field was irrigated with a center-pivot sprinkler irrigation system that applies one inch of effective water to a given point every three days, if required, i.e., it takes three days for the system to make a complete cycle around the field.

Irrigation was begun after June 30, whenever the soil-moisture profile in the active root zone was depleted to a given percentage of the field capacity in the active root zone. It was felt that the degree of stress incurred before July 1 was unusually small and irrigation after June 30 avoided a potential wetness problem due to spring rains added on top of irrigation.

RESULTS

Lamberton, Minnesota

The original SOIL MOIST I program was run for two soils found in the southwestern Minnesota area. One of the major soils in the area is Webster, another is Dickman sand. To obtain the irrigation response, the program is first run with the natural weather data that occurred for each year of record, 1960-78, then rerun again with the irrigation cycle included. The program produces a weighted stress-index value for each year run, which is used to compute yields.

For the Webster soil, the average yield computed for natural rainfall conditions was 119 bu/acre. The average yield with irrigation was 153 bu/acre.

On the Dickman sand, the average yield computed for natural rainfall conditions was 81.2 bu/acre. The average yield, with irrigation, was 153 bu/acre.

The results computed on these two soils are typical of what should be expected on a high-moisture capacity and low-moisture capacity soil in a climatic region where rainfall is not usually in great deficiency, but mid-summer periods of use greater than rainfall are expected. The average yield increase of 34 bu/acre on the Webster soil is comparable to that found in Iowa, in regions of comparable rainfall. Normal rainfall provides a significant soil-moisture reserve going into most years, and this reserve helps carry the crop through summer dry periods with only moderate yield reductions. On the average, only moderate response to irrigation should be expected on these high moisture capacity soils.

On the lighter soils, such as the Dickman sand, even though the soil may start at, or near, field capacity in the spring, the reserve is much smaller

and can rapidly be depleted if dry weather occurs. The yield response to irrigation on this type of soil is significant, even in regions of relatively high annual precipitations.

Fayette County, Illinois

The Brownstown Agronomy Research Center, Fayette County, Illinois is conducting experiments on the irrigation of Cisne and Hoyleton silt loams, with a claypan 24 inches or less below the surface. The years of record used were 1964-77, a total of 14 years.

Although all three soil moisture programs were run for comparative purposes, SOIL MOIST III was written to represent, in a simple program, the situation which most likely exists on the Cisne claypan soil of Illinois. With added moisture, each increment from top to bottom is allowed to reach field capacity, then additional moisture is used to fill each increment up to saturation from the bottom increment to the surface. Any moisture in excess of this amount runs off the area. Since the claypan soil has essentially zero percolation through the top of the claypan, all moisture retained above the claypan must be removed by evaporation and transpiration. All rooting and moisture extraction is limited to the layer above the claypan. Under natural rainfall conditions the average yield was 104 bu/acre. With irrigation, yield was estimated as 153.8 bu/acre, giving an increase of 49 bu/acre, with an average water use of 7.4 inches.* Increases ranged from 0 to 136 bu/acre. Water applied averaged 4.7 inches and ranged from 0 to 15 inches.

* Field plot studies optimizing seed, nutrients for high water conditions, and irrigation show a gain almost twice the predicted yield that was based upon normal operational procedure.

In soils with a claypan such as the Cisne, excess wetness must often be a problem in spring. The output from SOIL MOIST III was examined to obtain an estimate of years when excess moisture would be a problem, assuming the profile started at field capacity on May 5. Of the 14 years of data, 6 showed values of soil moisture above field capacity in some part of the profile. Four years showed values above field capacity occurring in both the two lower 6-inch increments for more than 8 days.

Conclusions

Supplemental irrigation on both light and heavy soils in the upper Midwest will increase average annual yields. On light soils (Dickman sand), the average yield increase was about 72 bushels/acre. Less increase was predicted on the heavier soils (Webster) where a predicted yield increase of 34 bushels/acre was determined.

V. OPTIMIZATION OF WATER USE AND DRAINAGE FOR FIELD CROP PRODUCTION ON CLAYPAN SOIL IN THE UPPER MIDWEST*

INTRODUCTION

There are about 10 million acres of fine-textured soils, also known as claypan soils, in the Midwest. These soils have a 6- to 18-inch layer of silt loam topsoil with a heavy clay subsoil. The topography associated with these soils is quite flat with usually less than 0.5 percent slope, and often groundwater supplies are limited. The crop yields on these soils are quite variable and usually low because of limited water management. With proper water management these soils can be very productive every year.

The area with the largest concentration of claypan soils is south-central Illinois. The mean annual precipitation in this area is 40 inches, which would be plentiful for crop production if it were properly distributed. Unfortunately, excess rainfall often occurs in the spring, contributing to a problem of excessively wet soils; and often there are several weeks without rainfall in the summer, causing drought. Periods of excessively wet soil and periods of drought often occur within the same growing season.

This project investigated combinations of both irrigation and drainage treatments in order to determine the best water management practices for field crop production in claypan soils in the upper Midwest. Four years of corn and one year of soybean yield data from forty field plots are presented. The irrigation treatments were sprinkler, furrow, and no irrigation; the drainage treatments were surface, subsurface, surface plus subsurface, and no drainage.

*This section summarizes the research of P.N. Walker; M.D. Thorne; E.C. Benham; and W.D. Goetsch; reported in Optimization of Water Use for Field Crop Production in the Upper Midwest, Research Report 159. Water Resources Center, University of Illinois at Urbana-Champaign, April 1981.

The project also developed a soil-moisture model and a treatment-yield model for irrigation and drainage on tight claypan soils. However, sufficient data was not available at the time of this report, and no definite conclusions could be drawn from the modeling portion of the study. The model will be verified as additional years of data are collected.

IRRIGATION AND DRAINAGE - THE POTENTIAL

The thin topsoil in claypan areas means that crop roots have only a small volume of soil from which to extract water between rainfalls. Therefore, irrigation is necessary to avoid plant stress between rainfalls and to maximize yields. The virtual absence of groundwater supplies in this area means that irrigation must rely on development of surface water resources. Irrigation must be done very efficiently in order to conserve water supplies. Nearly all of the current irrigation in the Midwest is by sprinklers. However, because claypan soils have an impermeable subsurface layer and a flat topography, they are particularly adaptable to furrow irrigation, which can be more energy efficient and more water efficient if tailwater is collected and reused. This research provides information necessary to irrigate this soil efficiently both by sprinklers and by furrow irrigation. Additionally, the demonstration function of these plots provides part of the impetus required for farmers to start choosing the more efficient furrow irrigation system.

A drainage system is needed for these soils to remove the excess water that exists nearly every spring and occasionally later in a wet cycle of a growing season. The subsurface soil layers are impermeable, thereby limiting natural subsurface drainage; and the surface topography is generally flat with occasional depressions, thereby limiting natural surface drainage.

The most commonly recommended drainage practice on this soil is surface drainage (land grading). Conventional subsurface tile drainage systems will not

work because of the clay subsoil. Surface drainage systems are not entirely satisfactory because the required grading removes the topsoil from some areas of a field and reduces its productivity. Additionally, surface drainage water is laden with sediments and nutrients. A subsurface drainage system could be more satisfactory. It would not require the movement of topsoil, and the drainage water would be virtually free of sediment and have a lower nutrient concentration.

The advent of corrugated plastic drain tubing makes possible the manufacture of lower-cost small-diameter subsurface drain lines. In claypan soil, these lines can be placed at close spacings above the claypan layer. This type of system was not feasible with conventional drain materials. This research project also addresses this type of drainage system and helps provide the information necessary to design an optimum subsurface drainage system.

When irrigation and drainage practices are integrated, the drainage water is stored in a surface reservoir and used for irrigation during drought periods. By recycling the water, the conservation of water supplies will be maximized because the amount of water leaving the farm will be minimized. This in turn will substantially lessen the potential for downstream flooding. Furthermore, the storage of this water will improve the quality of that water that does leave the land because the amounts of chemical and sediment pollutants leaving the farm will be greatly reduced.

METHODS

Forty field plots were established on a Cisne Association soil at the Brownstown Agronomy Research Center in southern Illinois. The center is located east of Vandalia, Illinois. The setup included replications of each of several irrigation and drainage treatment combinations for both corn and soybeans. These plots were instrumented for meteorological and water balance

measurements--that is, the amount of water entering, leaving, and being stored on each of the plots. Additionally, semiweekly plant leaf water potential and annual grain yields were determined for each plot.

These measurements were used to give annual averages of the effects of each of the treatment combinations. However, tens of years of data would need to be collected before the data could be expected to represent long-term average effects. This longevity would be required because yearly variations in the weather pattern are substantial.

Because such long-term studies are impractical, it was decided to use the meteorological water balance, leaf water potential, and yield measurements taken over a three-year period to develop relationships between (1) weather and soil moisture, i.e., water balance, (2) soil moisture, weather, and leaf water potential, and (3) leaf water potential and crop yield. These relationships would then be combined with historical weather data to predict the long-term effects of each water management combination treatment.

CONCLUSIONS

The principal conclusion of this study must be drawn from the yield data. First, the data indicate that both irrigation and drainage are needed on claypan soils in humid climates. Corn yields were increased by 13 bu/acre by drainage alone and 50 bu/acre by irrigation alone. Second, the data indicate that irrigation and drainage increase yield synergistically, with an average 92 bu/acre increase when irrigation and drainage are used together. Third, the method of irrigation, whether sprinkler or furrow, has little effect on yield. And fourth, the drainage type (whether surface, subsurface, or both) appears to have little effect on crop yield.

The fact that subsurface drainage might work equally as well as surface drainage has an important potential effect on water quality. Surface water carries sediment with it. Subsurface drain water, on the other hand, is free from sediment--which means that there is the potential for improving water quality while still maintaining yield, by using subsurface rather than surface drainage.

The fact that irrigation and drainage have a synergistic effect on yield adds impetus to the prospect of improving water quality and water-use efficiency. While it is unquestioned that storing drainage water and later using it for irrigation would improve water-use efficiency and downstream water quality, there is little chance of this improvement being instituted unless the process is also economically attractive to the landowner. This synergistic effect enhances those economic benefits.

The model methodology for predicting more accurate long-term estimates of treatment yields appears to be the best approach to the problem. Additional data are being collected in 1981, and the research will continue at least through 1983. Additional data should permit refinement of the models.

VI. THE ECONOMIC POTENTIAL FOR IRRIGATION ON CLAYPAN SOILS*

INTRODUCTION

The installation and operation of irrigation systems in the Midwest has expanded rapidly in the past decade. In Indiana, for example, the number of irrigated areas has increased from less than 40,000 acres in 1972 to approximately 70,000 acres in 1977. Similar increases have occurred in Illinois where irrigated acreage expanded from less than 54,000 acres in 1974 to approximately 131,000 acres in 1978. Increased interest in irrigation is occurring due to the variability of weather conditions and the increased financial risk associated with crop failure. Weather conditions in the Midwest during the 1970's, particularly the amount and distribution of rainfall during the year, matched much more closely the variability recorded for the 100 years of weather records than did the stable weather patterns of the 1950's and 1960's. This variability has increased the risk associated with the inability of the farm manager to control the moisture variable in the farm production process.

Economic risk in farming has increased for several reasons. Farm size has been increasing along with the degree of enterprise specialization. Also, risk has increased due to increase in input cost. Even though farm income has been on the rise due to higher domestic demand and increased exports, so has the

*This section summarizes the research of W.L. Miller; R.D. Clouser; P. Erhabor; and J. Sobek; reported in The Economic Opportunity to Irrigate Corn and Soybeans on Midwestern Claypan Soils, Technical Report 93. Water Resources Research Center, Purdue University, West Lafayette, IN, June 1981; and the research of R.L. Clouser; and W.L. Miller; reported in The Economic Consequences of Irrigating Corn on Fine Textured Soils in the Humid Midwest, Technical Report 96. Water Resources Research Center, Purdue University, West Lafayette, IN, April 1980.

value of agricultural land. The higher land prices combined with increases in other inputs, such as fertilizer and seeds, commits a farm operator to major cash outlays for crop production. With these high operating outlays financial losses may occur if drought conditions prevail. For those farmers with high debt to asset ratios, the consequences of crop loss may be financial disaster.

Substantial research has been conducted on the economic profitability of irrigation on coarse-textured soils in the Midwest. Irrigation systems have been adopted on these soils due to the production response of corn to water and the low cost of well water that generally is available at shallow depths.

However, limited research has been focused on fine-textured soils. Since these soils have high water-holding capacity, irrigation has not been needed in the humid regions to supplement rainfall. However, fine-textured soils with restricted zones for plant root development, such as claypan or fragipan soils, will have higher crop yields when irrigation is provided during the low rainfall periods of July and August. Recent agronomic data indicates corn on a claypan soil responds to irrigation. The research reported here is designed to examine the economic returns in the humid Midwest of irrigating fine-textured soil with a restricted root zone.

The objectives of this research are:

1. To utilize a micro-economic farm-planning model to analyze investments in irrigation technology and irrigation system operation suitable for midwestern agricultural operations.
2. To examine the relative profitabilities of dryland corn, dryland soybeans, irrigated corn, and irrigated soybeans on claypan soils.
3. To evaluate the economic potential for irrigating corn grown on claypan soils with alternative cost discount rate and yield assumptions.

4. To examine irrigation profitability on farm systems of several sizes, i.e., 640 acres, 160 acres, 120 acres, 80 acres and 40 acres.

5. To evaluate the economic potential of different sources of water for the irrigation system.

6. To assess the relative profitability of farms with mixed grain and livestock (hogs or cattle) as well as, cash grain operations.

THE MODEL

Mathematical programming models of a micro farm unit, producing grain and livestock, were used in this study. The math programming models maximize net farm revenue and include an investment model of irrigation activities. In addition, a fixed level of livestock has been determined exogenous to the model, but labor and feed activities for the livestock enterprise are endogenously deducted from available resources.

CONCLUSIONS

The results of this analysis show irrigation on claypan soils to result in higher net values of the annual discounted cash flows for farms of different sizes. In cases where 80-acre, 160-acre, and 640-acre farms were evaluated, the irrigated systems produced higher net returns to labor and management than did the dryland operations. The results of the analysis are summarized in Table 6.1 for both the 4 percent and 12 percent rates of discount. The relative ranks among systems are the same regardless of which rate of discount is used to make the comparisons.

These results indicate a potential exists for irrigation on small and medium size farms in claypan areas. The results only indicate potential because each farm situation must be evaluated on its own merits taking into consideration factors such as the distance from a water storage pond to the

Table 6.1. Comparison of the Alternative Types and Scales of Irrigation Systems*

System	Acreage	NPV† @ 12%	NPV† @ 4%
Dryland Corn and Soybeans	640	\$ 112,955	\$ 187,569
Irrigated Corn	640	155,530	248,308
Irrigated Corn and Soybeans	640	173,971	261,505
Irrigated Corn and Soybeans with Small Hog System	640	192,954	306,916
Irrigated Corn and Soybeans with Large Hog System	640	233,718	370,031
Irrigated Corn and Soybeans with Small Cattle System	640	260,752	411,565
Irrigated Corn and Soybeans with Large Cattle System	640	418,112	647,733
Dryland Corn and Soybeans	160	54,866	90,734
Dryland Corn and Soybeans	80	3,591	5,983

Irrigated Corn and Soybeans	160	174,062	108,738
Irrigated Corn and Soybeans	80	24,833	15,208
Irrigated Corn and Soybeans with Limited Labor	160	75,197	46,359
Irrigated Corn and Soybeans with Limited Labor	80	22,220	13,608

†Taken from Miller, et al 1981.

†Net present value.

fields to be irrigated, labor availability during the irrigation season, and access to capital to finance irrigation investments. The results indicate it appears to be worthwhile for the individual farmer operating on claypan soils to evaluate irrigation along with other alternative capital investments.

Although the net present values of the annual cash flows for irrigated production always exceed dryland, in a particular year dryland production could be more profitable. When rainfall is adequate during July and August for good crop production, dryland becomes more profitable than irrigated because no costs associated with irrigation are incurred. However, in other years of low rainfall or poorly distributed rainfall, substantial losses are incurred by the dryland claypan farmer. This clearly illustrates the insurance nature of irrigation over a period of years.

Soybeans appear to be a profitable crop for irrigation on claypan soils. This permits irrigators to rotate corn and soybean production, which permits them to achieve the higher yields associated with crop rotations in contrast to a continuous corn alternative.

Data were collected on several aspects of the irrigation program. On claypan soils water impoundment reservoirs cost slightly less than \$1.00 per cubic yard of earth moved in construction. About 3 cubic yards of water were impounded for every cubic yard of earth moved for these structures. Labor requirements for operation of a 160-acre center pivot system throughout the operating season averaged .372 hours per acre irrigated for a multiple pivot system. Labor requirements were .709 hours per irrigated acre for the multipivot 40-acre systems. Electric power costs ranged from \$516 to \$1293 per season with an average cost of \$858 for the electric utilities in the state of Indiana. Three-phase electric motors operated with Roto Phase Convertors from single-phase electric lines are the most economical source of power when three-phase lines are not available at the site.

VII. THE ECONOMICS OF IRRIGATING MEDIUM- AND FINE-TEXTURED SOILS IN MINNESOTA*

Previous studies of the profitability of irrigation in the upper Midwest have emphasized the coarse-textured soils in the glacial outwash areas. While relatively little experimental data has been available on the profitability of irrigating finer textured soils, some farmers have installed irrigation systems and have been using them to irrigate fine- and medium-textured soils in the area.

This study provided information on the type of irrigation systems being used and the increase in yields achieved by southern Minnesota farmers on fine- and medium-textured soils. The irrigators in 26 south central and southwestern counties were interviewed to obtain data on the irrigation systems being used, the amounts and timing of inputs that are used in the production of field crops, and the difference between irrigated and non-irrigated yields. The survey data are summarized in the second section of this report.

This study also provided estimates of the potential profitability of irrigating the major field crops on fine-to-medium textured soils in south central and southwestern Minnesota. Typical irrigation systems were defined based on the survey data. Current estimates of investment and operating costs were prepared for the three major field crops--corn, soybeans and alfalfa--produced in the area. The internal rate of return method was used to evaluate the profitability of investing in an irrigation system to produce corn and soybeans on alternative medium- and fine-textured soils. Comparable

*This section summarizes the research of V.R. Eidman and Paul N. Wilson, reported in The Economics of Irrigating Medium and Fine Textured Soils in Minnesota. Department of Agricultural and Applied Economics, University of Minnesota, St. Paul, MN, 1982.

estimates were not prepared for alfalfa because of the limited data on yield response to irrigation.

THE SURVEY

The Approach

The southwest and south central regions of the state were selected as the survey region because the predominant soil types in this area are fine-textured with high water-holding capacities. Available water-holding capacity (AWC), the portion of water in a soil that can be absorbed by plant roots, was chosen as the variable to differentiate between fine-, medium-, and course-textured soils. Soils with 6" or more of AWC in the upper 60 inches of soil (or to a limiting layer, whichever is shallower) were considered in this study.

Findings

The 40 farmers that were interviewed had a total of 49 irrigation systems. Center pivot distribution systems are the most popular with units ranging from 4-tower to 13-tower models. Thirty of the 33 center pivot systems were electrically driven, and the remaining three systems were driven by water pressure.

Field corn yields for moderate soils with 6-9 inches AWC increased 86 percent with irrigation. Lower relative increases of 44 and 41 percent were estimated for soils with high (9-12 inches AWC) and very high (over 12 inches AWC), respectively. While irrigators had less experience irrigating soybeans, they indicated soybeans do not respond as dramatically to irrigation. Yield increases of 25 to 33 percent per acre were recorded for the three AWC classes. Sufficient data was not available on alfalfa hay production to make comparable estimates for that crop.

A linear regression model was estimated to summarize the relationship between corn yield, available water-holding capacity, and the amount of rainfall during the growing season. The average corn yield data came from the respondents. As anticipated, AWC was not significant in explaining variability in irrigated corn yields. The coefficient on the amount of rainfall during the growing season (RAIN) was significant at the 5 percent level suggesting average irrigated yields increase with an increase in average growing season rainfall as one moves from west to east across the study area. As hypothesized, both AWC and RAIN were significant for non-irrigated yields.

The relationships indicate that as AWC increases, the corn yield differential due to irrigation decreases. An insufficient number of yield estimates were obtained for soybeans and alfalfa to estimate comparable equations for those crops.

PROFITABILITY ANALYSIS

Approach

The discounted cash flow or internal rate of return method was used to analyze the profitability of irrigating corn and soybeans on the soils having 6 inches or more of available water-holding capacity. This procedure involves calculating the annual cash inflows and outflows attributable to the investment over the planning period. Comparing the cash inflows and outflows for each year indicates if the investment is expected to generate enough additional revenue to cover the incremental operating costs, interest, and principal payments. This projected net cash flow or income also provides the basis for calculating the net present value (NPV) and the internal rate of return (IRR) of the investment. The net cash flow can be discounted by the minimum rate of return a producer is willing to accept to calculate the NPV.

If the NPV is greater than 0, the investment has a rate of return greater than the minimum return desired by the producer, while a negative NPV implies the investment has a rate of return below the desired rate. The IRR is that discount rate that equates the net present value of the cash flow stream to zero. This rate can be compared to the decision maker's opportunity cost of capital. If the IRR is larger (smaller) than the opportunity cost, then the investment is more profitable (less profitable) than the operator's alternative investments. The results of the analysis are presented as the internal rate of return to simplify comparisons of the profitability across soil situations. The reader is cautioned that while the internal rate of return may indicate an irrigation investment should be profitable over the planning period, large negative cash flows after income tax and loan payments may cause liquidity problems for operators during part (typically the early years) of the planning period. Unless cash is readily available from other enterprises, through short-term borrowing and owner savings, the investment may not be feasible even though it is profitable.

The analysis was based on a ten-tower electric-drive center pivot irrigation system. This was the most common system used by farmers surveyed. The system irrigates approximately 130 acres with water from a well having approximately 50 feet of lift and a pumping rate of 800 gallons per minute. The power source is a 75 H.P. electric motor.

The investment cost of the irrigation system was \$65,344. It was assumed the operator added as much to his total indebtedness as the initial investment in the system - the modal situation for farmers surveyed. The analysis assumes the loan of \$65,344 is amortized over 10 years at 12 percent interest. The individual is assumed to be in a combined federal and state marginal income tax bracket of 40 percent. The salvage value of the system was

estimated to be \$8,471 at the end of a 15-year planning horizon.

The analysis was based on the production of a corn-soybean rotation with 6 inches of water applied annually to corn and 3 inches to soybeans. Crop prices of \$2.50 per bushel for corn and \$6.00 for soybeans were used.

The internal rates of return were calculated for four soil types selected from both the southwest and south central areas. Yield differentials due to irrigation were calculated for corn. Soybean yields for the moderate AWC soils were assumed to be 35 bushels (non-irrigated) and 45 bushels (irrigated), while for high and very high AWC soils soybean yields were calculated at 40 bushels (non-irrigated) and 50 bushels (irrigated). Because the irrigation survey indicated new irrigators typically do not achieve the full irrigated yields the first two years, irrigated yields in years 1 and 2 were reduced to 90 percent of the predicted values. This reflects the learning that takes place in the shift from non-irrigated to irrigated production.

Findings

The internal rates of return are summarized for the eight soil types in Table 7.1. The rates of return for irrigation on moderate soils (AWC of 6-9 inches) vary from 12 to 26 percent. The heavier soils with more than nine inches of available water holding capacity produce an internal rate of return of below 12 percent, suggesting irrigation would not be a profitable investment for most producers on these soils.

All of the calculations of annual net cash flows after income taxes and loan repayment show some negative cash flows during the loan repayment period, with the larger deficits associated with the lower internal rates of return. The number of years with a negative net cash flow varies from 5 for the Hanska-Sparta soil to 9 for a Webster-Glenco soil. Irrigators of these soils

must be prepared to cover these negative cash flows from other sources if the investment is to be financially feasible.

The results of this analysis are sensitive to changes in the size of yield increases from irrigation, commodity price levels, input prices, the initial cost of the irrigation system, the method of financing the investment, and the individual's marginal tax bracket. However, the irrigation survey indicates the assumptions outlined in this report represent the modal situation of irrigators on medium- to coarse-textured soils in southern Minnesota.

Table 7.1 Internal Rates of Return for Typical Soil Types Being Irrigated in Southern Minnesota.

<u>Soil Type</u>	<u>AWC (inches)</u>	<u>Corn Yield Differential (Bushels)</u>	<u>IRR (Percent)</u>
South Central			
Hanska-Sparta	6.32	75	26
Minnetonka	9.48	56	8
Clarion-Nicollet-Webster	11.40	44	2
Webster-Glenco	12.36	38	-1
Southwest			
Clarion-Estherville	7.62	71	17
Estelline	8.40	66	12
Svea-Barnes	11.40	47	2
Moody-Primgar-Canisteo	12.36	41	0

VIII. EFFICIENT USE OF WATER FOR THE IRRIGATION OF ALFALFA IN THE NORTHERN PART OF THE UPPER MIDWEST*

INTRODUCTION

The objective of these studies was to develop information on soil-water-plant relationships for alfalfa in the northern part of the upper Midwest. Alternative systems of alfalfa management were tested under irrigation on both coarse- and fine-textured soils, having a range of water storage and profile characteristics. Research was conducted from December 1, 1978, to September 30, 1980, at Rosemount, Staples, St. Paul, and Becker, Minnesota.

PROCEDURES

Experiment I

Alfalfa-cutting management under irrigation was studied, using the variables of variety, fertility, and cutting management. Three irrigation regimes were used based on plant consumptive water use at various stages of growth. Detailed measurements of soil and plant moisture were obtained, and yield, forage quality, and root distribution data were collected.

Experiment II

Alfalfa varietal response to moisture stress was explored, using varieties with varying disease and dormancy reaction. These studies were carried out in both the greenhouse and field under conditions of moisture stress and irrigation, medium stress, and high stress to evaluate differences in water use efficiency.

*This section summarizes the research of Craig C. Shaeffer, as reported in a summary report on project B-120-ILL submitted to U.S. Department of the Interior; and the research of P.R. Carter, C.C. Shaeffer, and W.B. Voorhees reported in "Root Growth, Herbage Yield, and Plant Water Status of Alfalfa Cultivars," Crop Sci. 22: 425-27.

Experiment III

Irrigation scheduling systems were studied. Previously recommended full season irrigation procedures, which were based on consumptive use, were compared to alternative systems. Treatments included: (1) irrigation according to consumptive use; (2) irrigation limited to spring and early summer; (3) irrigation throughout the growing season but discontinued in fall; (4) irrigation according to consumptive use plus additional irrigation immediately following cutting. Yield, plant, and soil water status were collected.

Equipment and Facilities

Irrigation was by solid-set sprinklers on 30 ft. centers and was monitored by tensiometers and electrical resistance blocks.

RESULTS

Experiments conducted at Rosemount, Minnesota, on a silt loam soil indicated that irrigation could increase alfalfa yields; however, over a three-year period, an increase occurred in only one year. Irrigation resulted in decreased persistence of alfalfa particularly when in combination with fall harvesting and when non-winterhardy varieties were used (Table 8.1).

On a sandy loam soil at Staples, irrigation consistently increased alfalfa yield. Irrigated alfalfa dry matter yields were significantly greater for all harvest and K₂O treatments than for similar unirrigated treatments (Table 8.2). For most harvest and K₂O treatments there were no differences in yield between the one-half and full checkbook irrigation treatments, which resulted in annual applications of 26 and 53 cm of water, respectively.

For the unirrigated treatment, yields for the 540 lb K₂O/A treatment were significantly greater than for all other K₂O treatments. The H₁ harvest treatment (June 15, September 1, October 15) generally had greater yields than the H₃ treatment (June 1, July 15, and September 1).

Within the one-half checkbook irrigation treatment, yields for the 0 K₂O/A fertility treatment were not significantly greater than for the highest yielding unirrigated treatment (H₁, 540 lb K₂O). For the H₁ harvest treatment, yields did not increase significantly as K₂O fertility level increased above 180 lb/A, but for the H₂ (June 1, July 15, September 1, and October 15) and H₃ harvest treatments, the 540 lb K₂O/A treatment had greater yields than all other fertility treatments.

For the checkbook irrigation regime, forage yields for the H₁ harvest treatment of the 360 and 540 lb K₂O/A plots were greater than for the unfertilized H₁ harvest treatment. Yields for the 360 and 540 lb K₂O/A treatments subjected to the H₂ and H₃ treatments were not different and exceeded the 0 and 180 K₂O/A treatments.

With respect to alfalfa varietal response to irrigation, results of this research indicate that alfalfa cultivars vary in plant water potential and yield, especially when subjected to soil moisture stress and the differences related to root length and growth habit. Therefore, it appears that potential exists for improving the adaption of alfalfa to soil water deficits.

CONCLUSIONS

The best yields and persistence of alfalfa that were achieved in these studies under irrigation can also be achieved through the use of conventional management practices without irrigation. Additional research is necessary to define the most efficient irrigation strategies. These strategies were not possible to surmise within the time and financial limitations of this project. Application of variable irrigation levels have resulted in only limited differences in alfalfa yield (Table 8.3). These results have been consistently observed at the central Minnesota location.

There appears, however, to be a potential for improving the adaption of alfalfa to soil water deficits.

Table 8.1. Effect of irrigation and fall harvest treatments on alfalfa dry matter yield in 1980 and on residual yields in 1981, Rosemount, Minnesota.

Treatment	Cultivar	1980 yields		1981 yields [†]	
		Three harvests [†]	October 15	No fall harvests	Fall harvest
-----metric tons/ha-----					
Irrigated*	Agate	13.2	1.3	6.4	5.7
	Anchor	12.6	1.5	6.8	6.4
	Saranac AR	11.6	1.6	5.3	4.4
	Mean	12.5	1.5	6.2	5.5
Nonirrigated	Agate	8.6	1.9	7.5	6.8
	Anchor	9.4	1.9	7.2	6.6
	Saranac AR	8.5	2.4	7.7	6.2
	Mean	8.8	2.1	7.5	6.5
L.S.D. (0.05)		1.0	0.7	1.3	

[†]Harvests taken June 1, July 15, and August 31.

[†]Yields for two harvests as influenced by 1980 treatments.

*20 cm of irrigation was applied in 1980; no irrigation was applied in 1981.

Table 8.2. Effect of irrigation, harvest and K₂O fertility treatment on dry matter yield of alfalfa at Staples, Minnesota.¹

Irrigation treatment ²	Harvest treatment ³	K ₂ O level (lb/A)				\bar{x}
		0	180	360	540	
		T/A				
Unirrigated	H ₁	2.99	3.35	3.37	4.42	3.53
	H ₂	2.93	2.91	3.04	4.00	3.22
	H ₃	2.42	2.71	2.83	3.55	2.88
	\bar{x}	2.78	2.99	3.08	3.99	
Irrigated (1/2 check- book)	H ₁	4.56	5.13	5.03	5.13	4.96
	H ₂	4.18	4.95	5.24	6.05	5.11
	H ₃	4.40	4.92	5.04	5.91	5.07
	\bar{x}	4.38	5.00	5.10	5.70	
Irrigated (checkbook)	H ₁	5.09	5.35	5.76	5.51	5.43
	H ₂	4.61	4.82	6.00	6.18	5.40
	H ₃	4.73	5.33	6.07	5.79	5.48
	\bar{x}	4.81	5.17	5.94	5.83	

L.S.D. (.05) = .37 is appropriate for comparison of two three-way interaction (irrigation x harvest x K₂O) means within an irrigation regime.

¹Values are a mean for two alfalfa cultivars.

²Irrigation according to the checkbook method resulted in the application of 53 cm of H₂O. Irrigation at 1/2 checkbook resulted in a 26 cm H₂O application.

³Harvest measurements: H₁ = June 15, September 1, October 15; H₂ = June 1, July 15, September 1, October 15; H₃ = June 1, July 15, September 1.

Table 8.3. Effect of irrigation treatments on alfalfa dry matter yield and water applied at Becker, Minnesota, 1981.

	June 8	Alfalfa yield		Total	Irrigation Applied
		July 15	August 20 ⁺		
	-----metric tons/ha-----				cm
1. Unirrigated check	2.1	2.2	1.7	6.0	0
2. Full irrigation ⁺	2.8	2.7	3.1	8.6	18.9
3. 33% of full irrigation	2.7	2.6	2.9	8.2	7.6
4. 66% of full irrigation	2.7	3.2	3.4	9.3	12.1
5. Full irrigation only after harvest [‡]	2.1	2.3	1.8	6.2	4.5
6. 33% of full irrigation and full irrigation after harvest ⁺⁺	2.4	2.7	2.8	7.9	8.9
Checkbook method*	2.7	3.0	3.2	8.9	16.3

+ Three harvests were taken at 1/10 bloom.

[‡] Irrigation to field capacity when soil reached 50% AWD. Soil moisture level monitored via neutron probe.

⁺⁺Received no or 33% of full irrigation during the growing season and full irrigation only after harvest.

* Irrigation by method of Werner, 1978. (Minnesota Misc. Pub. 160).

IX. GENERAL CONCLUSIONS

From this series of studies the following general conclusions can be drawn:

1. There are many areas of the Midwest with natural groundwater resources of sufficient yield and quality to support the development of irrigation. In addition, adequate surface water resources may be developed for irrigation development, especially in the southern one-half of the region.

3. Soil moisture models indicate that only moderate yield response to irrigation can be expected on high moisture capacity soils. On lighter soils and claypan soils, yield response is significant, even in regions of relatively high annual precipitation.

4. Although irrigation and drainage on claypan soils individually increase corn yields, together they create a dramatic synergistic response. The method of irrigation and the drainage type have little effect on crop yield.

5. It would appear that investments in irrigation would not be profitable for individual farmers operating on heavy soils with available water-holding capacities of more than 9 inches. It does appear to be economically worthwhile for the individual farmer operating on moderate soils with available water-holding capacities of 6-9 inches or on claypan soils to evaluate capital investments in irrigation along with other capital investments. Each farm situation must be evaluated on its own merits, however, taking into consideration a variety of physical and financial factors.

6. The best yields and persistence of alfalfa that were achieved in these studies under irrigation can also be achieved through the use of conventional management practices without irrigation. It appears, however, that a potential exists for improving the adaptation of alfalfa to soil water deficits. Further research is needed to verify these conclusions.

X. REFERENCES CITED

- Anderson, C.E. 1975. A Water Balance Model of Agricultural Watersheds on Deep Loess Soils. Unpublished Ph.D. Dissertation, Kansas State University, Manhattan, Kansas.
- Huff, F.A.; and Changnon, S.A., Jr. 1972. Evaluation of potential effects of weather modification on agriculture in Illinois. J. Appl. Meteor. 11:376-84.
- Irrigation Journal. 1976-79. Irrigation Survey. Survey Issue, Volumes 26-29.
- Krane, S.; and Haas, J.E. 1976. Climate and Food. Rept. of the Comm. on Clim. and Wet. Fluctuations and Agric. Prod., Washington, D.C.
- Meinzer, O.E. 1940. Groundwater in the United States. U.S. Geological Survey Water Supply, Paper 836. U.S. Geological Survey, Washington, D.C.
- Murray, C.R. and Reeves, E.B. 1977. Estimated Use of Water in the United States in 1975. Geological Survey Circular 765. U.S. Geological Survey, Washington, D.C.
- Shaw, R.H.; Flech, R.E.; and Duncan, E.R. 1972. Soil Moisture Available for Plant Growth in Iowa. Iowa Agricultural and Home Economics Experimental Station and Cooperative Extension Service. Special Report No. 70. Iowa State University, Ames, Iowa.
- Thomas, H.E. 1952. Groundwater Regions of the United States - Their Storage Facilities. In: The Physical and Economic Foundation of Natural Resources, Vol. III.
- United Nations. 1976. Ground Water in the Western Hemisphere. Natural Resources/Water Series No. 4, United Nations, New York.
- U.S. Water Resources Council. 1978. The Nation's Water Resources 1975-2000: Second National Assessment, Vol. I. U.S. Water Resources Council, Washington, D.C.

XI. PUBLICATIONS RESULTING FROM PROJECT RESEARCH

- Austin, T.A.; Anderson, C.E.; Johnson, H.P.; Shaw, R.H.; Golchin, J.; Shahvar, Z.; Arjmand, O. 1982. Efficient Use of Water for Irrigation in the Upper Midwest, ISWRI-117. Ames: Water Resources Research Institute, Iowa State University.
- Carter, P.R.; Sheaffer, C.C.; Voorhees, W.B. 1982. Root growth, herbage yield, and plant water status of alfalfa cultivars. Crop Science 22:425-427.
- Clouser, R.L.; Miller, W.L. 1980. The Economic Consequences of Irrigating Corn on Fine Textured Soils in the Humid Midwest, Technical Report 98. West Lafayette: Indiana Water Resources Research Center, Purdue University.
- Miller, W.L.; Clouser, R.L.; Erhabor, P.; Sobek, J. 1981. The Economic Opportunity to Irrigate Corn and Soybeans on Midwestern Claypan Soils, Technical Report 93. West Lafayette: Indiana Water Resources Research Center, Purdue University.
- Thorne, M.D. 1979. Moisture management. Crops and Soils Magazine, December.
- Walker, P.N.; Thorne, M.D.; Benham, E.C.. Irrigated Corn on an Illinois Claypan Soil, Paper No. 81-2093. For presentation at the 1981 Summer Meeting of the American Society of Agricultural Engineers, June 21-24, 1981.
- Walker, P.N.; Thorne, M.D.; Benham, E.C.; Goetsch, W.D. 1981. Optimization of Water Use for Field Crop Production in the Upper Midwest, UIUC-WRC-81-0159. Urbana: Water Resources Center, University of Illinois at Urbana-Champaign.
- Wilson, P.N.; Eidman, V.R. 1982. The Economics of Irrigating Medium and Fine Textured Soils in Minnesota, Economic Report ER81-8. St. Paul: Institute of Agriculture, Forestry and Home Economics, University of Minnesota.