Computer simulation of the irrigation potential of corn on high water-holding capacity soils in Iowa

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Computer simulation of the irrigation potential of corn on high water-holding capacity soils in Iowa

by

David Christopher Nielsen

A Thesis Submitted to the Graduate Faculty in Partial Fulfillment of The Requirements for the Degree of MASTER OF SCIENCE

Department: Agronomy
Major: Agricultural Climatology

Signatures have been redacted for privacy

Iowa State University Ames, Iowa

1979
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INTRODUCTION

One of the more important factors influencing the final yield of a corn crop is moisture stress. Stress can affect the processes of photosynthesis and respiration; it can affect growth, which provides synthesizing tissue; and it can affect reproduction, which provides the sink for the storage of photosynthate. In an area such as Iowa where corn is grown under a high level of management and where 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.

In most of the humid and subhumid area of the United States the annual rainfall is generally great enough to support sustained production of crops. Short periods of drought are common, however, and supplemental irrigation may provide the method for reducing or eliminating moisture stress as the major factor limiting corn yields in Iowa.

The purpose of this study is to determine by computer simulation how irrigation would affect the occurrence of moisture stress in corn grown on high water-holding capacity soils in Iowa, and how the removal of moisture stress by irrigation would affect final corn grain yields.

Two situations will be considered:

1. Irrigation under a high level of management in
which irrigation begins when the available moisture in the active root zone falls below 75% of the available moisture at field capacity.

2. Irrigation under a lower level of management in which irrigation begins when the available moisture in the active root zone falls below 50% of the available moisture at field capacity.

Also the effect of irrigation on the amount of water which percolates through the profile is examined. Finally, an attempt is made to estimate the effects of preseason irrigation on moisture stress, later irrigation amounts, and percolation.

Iowa provides an interesting situation for testing the effects of irrigation on moisture stress since within the state borders are areas in which excess moisture may be a problem, as in southeastern Iowa, as well as areas where moisture shortages occur with seasonal regularity, as in northwestern Iowa.
LITERATURE REVIEW

Water Use By Corn

Much research has been conducted to determine how much water is needed by a corn crop during a growing season. A partial review of the extensive literature regarding water use by corn follows.

According to Rhoades and Nelson (1955), irrigated corn used 16 to 25 inches of water during the growing season, although amounts of up to 33 inches and as low as 12 inches have been reported. Frequent irrigations or rains, or a combination of both, tended to increase consumptive use of water through greater evaporation. Rhoades and Nelson also state that any factors, such as irrigation practice, stand, and soil fertility treatment, that promote growth will also increase the consumptive use of water by corn.

Power et al. (1973) also found that total water use was generally lowest for dryland treatments and usually increased as irrigation amount increased. In a study of various irrigation methods in eastern North Dakota they found that the total seasonal water use by corn ranged from 7.5 inches under a dryland condition to 21.3 inches under a full irrigation scheme.

The increase in consumptive use under irrigated conditions was also noted by Moolani and Behl (1968). They
determined that consumptive use was highest where maximum irrigation water was applied. They further concluded that most crops use the water they receive and not necessarily what they really would consume if water were unlimited.

In a study on the effects of severe moisture stress on corn, Robins and Domingo (1953) reported that water use by corn which was kept well watered to tasseling and then irrigated, as well as for one treatment which was well watered only after tasseling, was approximately 22.2 inches.

Other workers have found similar seasonal water use values for corn. Using meteorological data, Denmead and Shaw (1959) estimated evapotranspiration by corn at 17.3 inches. Values of 17.7 inches and 15.75 inches for evapotranspiration were found by Doss et al. (1962) and Schleusener and Kruse (1963), respectively.

In reviewing the work of a number of researchers, Downey (1971) states that fairly consistent figures for seasonal water use by corn have been found. The majority of figures quoted are within the range of 15.75 to 23.50 inches. He concludes that a crop of corn will use $20 \pm 4$ inches of water from planting to maturity. Over large areas this will probably rise to $27 \pm 6$ inches because of operational losses. The actual amount will vary with the location and more specifically with the potential evapotranspiration at that site. The hotter and drier the region, the greater the upward bias
on the figure quoted, and the cooler and wetter the region, the greater the downward bias.

These results are in good agreement with irrigation work on corn done by Haise (1958) at three locations in North and South Dakota in the early 1950's. He found that the average seasonal consumptive use ranged from 16.6 to 21.1 inches. Shaw (1977) agrees that consumptive use by corn is ordinarily 16 to 25 inches.

Shaw et al. (1958) estimated the water use balance for corn in Iowa where use is composed of evapotranspiration, runoff, and percolation. They found that normal precipitation for the period of April 15 through November 1 was 23.6 inches while the average use for the same period was 25.1 inches. Average use was greater than or equal to normal monthly precipitation in June, July, and August. It appears as if the average seasonal deficit of 1.5 inches could easily be made up for by normal soil-moisture reserves. Unfortunately, average conditions seldom occur and many times during a growing season a corn crop may run short of moisture for a period of time. Later, excess rains may make the seasonal water balance look better, but the moisture-stress damage has already been done to the plant and a yield loss dependent on the time and severity of the stress will result.
Moisture Capacities of Iowa Soils

The amount of water that a soil can store in a form available for plant use is known as the available water-holding capacity of the soil. The available water-holding capacity is a very important soil characteristic. Where irrigation is used to grow crops the amount and frequency of water application are determined to large extent by the available water-holding capacity of the soil. Where crops are grown under dryland conditions the available water-holding capacity is a major factor determining how long a dry period the plants can tolerate. Available water-holding capacity is dependent upon a number of soil characteristics including soil texture, type of clay, structure, organic-matter content, and the thickness and sequence of layers in the soil profile (Thompson and Troeh, 1973).

According to Shaw et al. (1972), the plant-available soil moisture (moisture above the wilting point) in the top five feet of the soil profile on April 15 averages from less than 5 inches in northwestern Iowa to almost 11 inches in east-central Iowa. Soil moisture generally shows an increase to early June, then decreases during the summer months. From April 15 to June 1, soil moisture has shown an average increase of 0.6 inch. From June 1 to September 1, it has shown an average decrease of 3.7 inches, with the greatest decrease occurring in July. From September 1 to November 1, soil
moisture increased an average of 2.1 inches, with a further increase of 1.0 inch occurring from November 1 to April 15. Plant-available (PA) and wilting-point (WP) values reported by Shaw et al. (1972) for Iowa soils at locations pertinent to the present study are given in Table 1.

Wynne (1976) looked at soil-moisture characteristics of some common Iowa soils. He gives discrimination curves (evapotranspiration vs. % available soil moisture) which show the degree to which moisture is held in the soil (i.e., how hard it is for a plant to remove water from the soil).

The soils studied fell into three general groups. The Waukegan, Galva, and Fayette curves were similar and, in general, required the highest percentage of available soil moisture to prevent wilting. Taintor, Albaton, Nicollet, and Huntsville fell into a separate, intermediate group, while the Sparta and Colo soils resembled each other to comprise the third group. Moisture was most readily available in the Sparta soil, but as expected, it held a very low amount of water.

In the Corn Belt, soil-moisture reserves at the start of the growing season can be greatly different from place to place and from year to year. The normal situation is to have adequate to excess soil-moisture reserves in the eastern part of the Corn Belt, and adequate to deficient reserves in the western part. Some of the factors which influence the spring
Table 1. Plant-available (PA) and wilting-point (WP) values (in inches) used for different soils. Plant available water assumes no free water in the profile (after Shaw et al., 1972).

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soil-moisture reserves are carry-over of moisture from the previous crop season, or accumulations of moisture that may occur during the fall, winter, and early spring. Since evaporation rates in the fall are less, precipitation during this time may be quite efficient for increasing soil-moisture reserves (Shaw, 1977).

Zanzalari (1973) studied the influence of spring-season soil moisture on seasonal moisture stress in Iowa and concluded that with a given amount of precipitation, soils with a higher field capacity will record a lower stress index value when spring reserves are near capacity, but these same soils will have a higher index than a light soil when spring reserves are low. The effect of field capacity increases with decreasing precipitation. He also found that the significance of lowering the starting soil-moisture reserves was least in central Iowa, which has a lower capacity soil, and increases most rapidly to the southeast and northwest.

Effects of Moisture Stress on Corn Yields

According to Shaw and Laing (1966), moisture stress is the result of an imbalance between the supply furnished by the soil water and the amount needed by the plant as determined by the atmosphere, assuming a complete crop cover. Downey (1971) reviews much of the work on moisture-stress effects on corn and concludes that growth is reduced before
high values of stress are reached. Moisture stress interrupts photosynthesis and checks growth until turgor is restored to the plant by removal of moisture stress. Downey also states that where light is not limiting, photosynthesis decreases with increasing water deficits. It is therefore probable that maximum biological productivity will be obtained from a crop which is not subjected to water stress.

A number of researchers have looked at the effects of moisture stress on the corn crop and its yield. Shaw (1977) reviews much of this work. Most researchers find basically the same results. Briefly, some of these results are that the period of tasseling, silking, and pollination is a very critical stage in the growth of the corn plant. In the Corn Belt this stage occurs, on the average, in the latter part of July.

Claussen and Shaw (1970) report that moisture stress imposed at silking caused various yield reductions ranging from 3% to 7% per day of moisture stress. Mallett (1972) found similar results. He reported that four days of stress caused an average yield reduction of 4.3% per day of stress at each of the times that stress was imposed. In another experiment he found that the reduction was 4.1% per day of stress.

Robins and Domingo (1953) reported that depletion of soil moisture to the wilting percentage for 1 or 2 days
during the tasseling period resulted in as much as 22% yield reduction, while depletion to the wilting point for six to eight days gave yield reductions of about 50%. Denmead and Shaw (1960) found similar yield reductions of approximately 51% when moisture stress was imposed in the field. It was felt that the embryonic stage was mainly responsible for the large yield reductions due to its high sensitivity to moisture stress.

Even small amounts of moisture stress at critical time periods will affect yields. Colville et al. (1964) in experiments with irrigated corn and variable plant populations, hybrids, and productivity levels concluded that in many experiments in which rainfall had been considered ample, temporary moisture shortages reduced yields. Similar results were found by Beer et al. (1967) working on irrigated corn in Iowa. They found that even corn which was irrigated and had soil-moisture reserves maintained at a high level underwent moisture stress due to high atmospheric demand resulting in yield losses.

Denmead and Shaw (1960) found that moisture stress was also important in reducing corn yields when it occurred during the maturation or grain-filling stage. They found a yield reduction of 21% due to moisture stress during the ear-filling period, but reductions were smaller than for stresses imposed during tasseling and silking.
According to Shaw (1977), the susceptibility of the corn plant to moisture stress at silking is primarily due to the fact that in the late vegetative stage corn plants grow very rapidly. The water balance becomes negative during this time; i.e., the consumptive use is greater than rainfall so that the plant is depending entirely on soil-moisture reserves to make up the deficit. If soil-moisture reserves are low and the plant is losing water faster than it can extract it from the soil, then moisture stress occurs. The effect of this moisture stress is to delay silking by approximately six to eight days while affecting the time of tasseling very little (Mallett, 1972). The result is that many ovules are not fertilized and do not develop into mature corn kernels. The end result is an increased number of barren stalks and poorly filled ears reducing final grain yield.

Previous Irrigation Work Done in Humid and Subhumid Areas, Including Iowa

The question that inevitably arises when someone proposes to irrigate in the humid or subhumid regions of the United States is, "Why do you need to irrigate in a region where you already get enough seasonal moisture to grow a crop?" According to Tharp and Crickman (1955), some of the factors that have encouraged supplemental irrigation in the humid areas are drought periods; increased yields with
irrigation; production of products of higher quality; better information on moisture requirements of crops; relatively high farm incomes which have favored investment in irrigation systems; and improved irrigation equipment, particularly portable, lightweight, aluminum pipe, couplers, and sprinklers. In more recent years the development of large, labor-saving, center-pivot sprinkler irrigation systems has greatly stimulated interest in irrigation in subhumid regions of the United States. Schwab et al. (1958) add that increased use of fertilizers and development of better crop varieties have also led to increased irrigation in humid and subhumid regions.

Supplemental irrigation is practiced in the eastern United States with the idea of improving the existing type of production rather than making it possible to practice a new kind of agriculture, as is typical in the western United States. Rhoades and Nelson (1955) state that irrigation changes corn from a marginal to a profitable crop in semiarid regions, and it removes the ever present hazard of drought in the subhumid area and the humid east. They also state that benefits from irrigating corn vary from year to year in the subhumid and humid sections. Tharp and Crickman (1955) conclude that experimental work and the experience of many farmers have proved that supplemental irrigation will produce additional yields of crops and pastures in most years.
in humid areas. Haise (1958) provides examples of many cases which emphasize the importance of irrigation in stabilizing agricultural production during periods of subnormal rainfall.

Shaw (1977) states that a summer rainfall of six inches is about the lower limit for corn production without irrigation, but yield responses to irrigation are obtained with much higher summer rainfall, the response depending upon rainfall distribution and soil-moisture reserves.

Dale (1964) reports that for corn to avoid stress four out of five years, 95% of the available soil moisture would have to be present from July 15 to August 15. Daily root zone estimates, however, showed less than 60% present during the period for over half of the years considered. Iowa, it was concluded, does have a good risk of moisture stress during critical corn growth periods. It therefore seems that irrigation might offer a means of reducing moisture stress in corn in many years.

Rhoades and Nelson (1955) report results of irrigation experiments on corn in South Dakota, Georgia, and Nebraska. Experiments at the Redfield Development Farm in South Dakota showed increases in yield due to irrigation of 117 and 27 bushels/acre following alfalfa in years of below normal and above normal rainfall, respectively. At Athens, Georgia, the increases in yield resulting from irrigation ranged from less than 6 bushels/acre in years with nearly ample rainfall to 64
bushels/acre in years of droughts. Three irrigations that maintained a high moisture level from tasseling through silk- ing in Nebraska produced 144 bushels/acre, but if those same three irrigations occurred all before tasseling the yield was only 118 bushels/acre. In another experiment in Nebraska, a yield of 69 bushels/acre was obtained where moisture was de- ficient most of the growing season, compared to a yield of 153 bushels/acre when moisture was adequate. Rhoades and Nelson (1955) came to the conclusion that such results as those given above suggest that farmers in the subhumid region can benefit each year and that farmers in the humid regions can benefit most years from irrigating corn.

Power et al. (1973) experimented with irrigation in eastern North Dakota by applying water to corn plots at the rate of 1.5 cm/hour with a rotating-boom sprinkler. Either 6 cm or 9-12 cm of water were applied per irrigation. These application rates approximated the maximum quantity of water applied by center-pivot sprinklers and the minimum that can be applied with gravity systems, respectively. Seasonal ir- rigation was applied whenever about 50% of the available soil water within the active root zone was depleted.

Results suggest that stored water, growing season pre- cipitation, and added irrigation water are all equally ef- fective in enhancing crop production, and, within the range studied, one can be substituted for the other. These results
also suggest that such factors as amount of water added per event and frequency or timing of events may be of less importance than in more arid climates.

Other results of Power et al. (1973) show that water added after harvest was not reflected in soil-water content by seeding time the following spring or in increased crop yields, indicating that fall irrigation was of little value. Willis et al. (1961) in a study also in eastern North Dakota report similar results. They found that when soil-water content was increased in the fall, soil temperatures were reduced, soil warming in the spring was delayed, and runoff was increased. In view of these results and because fall irrigation failed to increase materially soil-water storage in the spring, Willis et al. conclude that fall irrigation is a very questionable practice for subhumid regions. Furthermore, where the irrigation water supply is limited, fall irrigation results in waste of water.

Research on irrigation of corn at Conesville and Ankeny, Iowa, from 1951 to 1955, is reported by Schwab et al. (1958). The Conesville experiment was located at the Southeastern Iowa Experimental Farm. The soils of the experimental plots are loamy sands and are fairly representative of relatively large areas of sandy soils throughout eastern Iowa. Drainage and aeration are very good. The infiltration rate is very rapid and may exceed an inch per hour. The soil can only
hold about one-half inch of water per foot in a form available for plant use. Wind erosion is a problem, as is fertility.

Portable circle-sprinklers were used for the irrigations. In 1951 the growing season was wet and cool, so there was very little need for irrigation. The five, two-inch irrigations gave no yield response over dryland yields. In 1952 yields were higher on all the irrigated plots than on the nonirrigated plots except for the low stand-low nitrogen plot. The maximum yield increase from irrigation was about 45 bushels/acre for 180 pounds of nitrogen at the high stand level. In 1953 the irrigated plot yields were considerably higher than those on the nonirrigated plots at all fertility and stand levels. In 1954 corn that was irrigated only during the silking period showed corn yields nearly the same as those from the nonirrigated plots. But the yields from plots with full-season irrigation were considerably higher than from the nonirrigated plots at both stand levels. Without irrigation there was essentially no response to added nitrogen. Also, without nitrogen there was only a very small increase in yield from irrigation. The 1955 results again show irrigation significantly increased yield and the effectiveness of nitrogen fertilizer. Also, irrigation at silking time compared with no irrigation resulted in average increases in yield of 8.5 bushels/acre for the two highest
fertility treatments at all stand levels, but only 2 bushels/acre with no nitrogen.

In most of the cases studied at Conesville the yields were depressed on the nonirrigated plots as stand levels were increased. Yields were not depressed by increasing the stand levels on the irrigated plots. Thus there was a tendency for the yield differences between irrigated and nonirrigated plots to be greater at the higher stand level. The effect of irrigation at different nitrogen levels varied from year to year partly because of differences in initial fertility level.

Furrow irrigation was used on the Ankeny plots. The plots were irrigated when the soil moisture dropped to 60% of the total available to plants in the top three feet. In 1954 irrigation resulted in a significant yield increase on the fertilized plots but not on the unfertilized plots. There was also a significant increase in yields at high stand levels on the fertilized plots but not on the unfertilized. The increase in yield with increasing stand is confined to the unirrigated fertilized plot. The lack of response with increasing stand on the irrigated and fertilized plots was explained by the fact that August rains caused excess moisture to pond in the furrows causing some plant damage. Corn yields were depressed on the unfertilized irrigated plots at higher stand levels due to a severe nitrogen
Table 2. Corn yield increases at Ankeny, from irrigation and nitrogen fertilizer for 1954 (average of all stands) (Schwab et al., 1958)

<table>
<thead>
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<th>Response to nitrogen</th>
<th>bu/acre</th>
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<tbody>
<tr>
<td>a. No nitrogen</td>
<td>5.4</td>
</tr>
<tr>
<td>b. 160 lbs. nitrogen/acre</td>
<td>19.3</td>
</tr>
<tr>
<td>Response to 160 lbs. nitrogen/acre</td>
<td></td>
</tr>
<tr>
<td>a. No irrigation</td>
<td>29.2</td>
</tr>
<tr>
<td>b. Irrigated</td>
<td>43.1</td>
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deficiency, a condition intensified by the excess water. Without adequate nitrogen, irrigation did not result in a significant yield increase. Yield increase results are shown in Table 2.

Since rainfall was below normal during the growing season in 1955 at Ankeny, response to irrigation was much greater than in 1954.

The response of corn to irrigation in both 1954 and 1955 at Ankeny should be noted. In 1954 rainfall was above normal for the entire season, but even under these conditions of abnormal rainfall on a soil that has a high water-holding capacity, it was possible to increase yields slightly with irrigation. Schwab et al. (1958) conclude that some increase
in corn yields can be expected on most well-drained soils in most years. Maximum response should normally be expected from sandy soils since they have the lowest water-holding capacity and cannot carry the crop through a drought period as well as a medium or fine-textured soil. The magnitude of the response will be greater on sandy soils than on medium to heavy textured soils.

The Conesville and Ankeny data both indicate that for maximum yields on irrigated land, higher stand and fertility levels are needed than on nonirrigated land.

Schwab et al. (1958) indicated that, at the time of their study, irrigation of corn was expected to increase in Iowa, especially along the Mississippi and Missouri rivers. Suitable conditions for irrigation also exist, they said, to a more limited extent along other major Iowa streams.

Beer et al. (1967) report on irrigation work in Ames, Iowa, on a Colo clay loam during the period of 1956 to 1961. The results of the study show that there was generally a net increase in corn yields due to irrigation over the six-year study period. The highest yields from the unirrigated plots were compared to the highest yields from the irrigated plots as a measure for evaluating the yields that a good manager could expect with and without irrigation. Without irrigation, the highest yields obtained averaged 108 bu/acre and ranged from 33 to 147 bu/acre. With irrigation, yields
averaged 131 bu/acre and ranged from 109 to 147 bu/acre. Thus, without irrigation, there was a range of 114 bu/acre, but under irrigation this range was reduced to 38 bu/acre. Average corn yields for the six-year period were 23 bu/acre higher under irrigation as compared with the "high-management level" unirrigated corn.

Similar moisture-stand-fertility relations were found in this study as in the Conesville and Ankeny irrigation experiments. The response to irrigation was usually greater at higher rates of nitrogen fertilization and at plant populations of 15,000 plants/acre or more. The magnitude of the response to irrigation was greatly influenced by the year-to-year climatic variation.

Results of the irrigation effects on corn yields indicated that the optimum moisture condition on Colo clay loam for years with near-normal rainfall was at or near the 60% available-moisture content. It was found that the more irrigation water that was required to maintain soil moisture above the 60% available-moisture capacity, the lower were the yields obtained under irrigation. The extremely good agreement between irrigation water and yield reductions indicates that there are climatic limitations that cannot be completely removed through irrigation. Extremely high temperatures during July could be one of the more important climatic factors that lower yields even when there is ample
moisture in the soil.

Beer et al. (1967) conclude that for most years in central Iowa on well-drained, fine-textured soils, some response to irrigation maintained at 60% of the available-moisture content level may be expected.

Corn yields were depressed in all cases when the soil was allowed to dry below 60% of the available moisture-holding capacity of the soil in the rooting zone of the corn plant. There was no advantage in maintaining the soil moisture above the 60% available level.

Results of Beer et al. (1967) show that irrigation with high soil fertility increased yields most years even when above normal growing-season moisture was present. It was also concluded that one would expect the yield responses of corn to irrigation to become more frequent in the drier and warmer areas of the state.

Predicting Yields From Weather Events

For many years the relationships of weather events to corn yields have been studied and correlated. In most cases the primary objective of these studies was to provide a method of forecasting yields with readily available weather data. A short review of some of the literature dealing with these methods and studies is given below with emphasis on those studies which deal with relationships of the type used
to estimate yields in the current study.

Morris (1972) reviews a great deal of literature dealing with regression models involving weather variables to predict corn yields. Much of the work reported indicates that many researchers feel that an adequate prediction of corn grain yields requires a multiple linear regression expressing the effects of several weather variables rather than a simple linear regression with one weather variable (Barger and Thom, 1949; Ewalt et al., 1961; Houseman, 1942; Sanderson, 1954).

The reason for this feeling is quite well-described by Kincer and Mattice (1928) who state that,

Weather, in the aggregate, for a given period of time as affecting plant growth, is a composite of many phases, such as temperature, rainfall, sunshine, wind, relative humidity, etc. There are also subphases, such as the mean temperature, mean of the daily maxima and the daily minima, mean daily range, etc. Growing crops are influenced more or less by all of these phases which, in combination, make up the weather of the season (p. 53).

Kincer and Mattice (1928) also discuss the critical periods of growth during which certain weather influences are more marked than during other times. They state that these critical periods, in some crops at least, are of comparatively short duration and require the use of weather variates based on similar short intervals of time so that their importance will be reflected in the final result.
Kincer and Mattice conclude that (1928):

\[ \ldots \text{the limitations of statistical correlations in studying the influence of weather on crops arise mainly due to the large number of weather phases, all, or most of which, apparently have more or less influence on yield, and also because of the varying importance of different periods of growth, necessitating the use of comparatively short time intervals (p. 53).} \]

They describe a study of weather and spring wheat yields in North Dakota in which only 5 of 15 original weather variables are retained in the final regression equation due to the close relationship between and relative unimportance of many of the variables. A similar study of weather effects on corn yields in Ohio showed the original 24 weather variables looked at finally reduced to six. The result was a raising of the combined correlation coefficient from 0.66 to 0.93.

According to Morris (1972), analysis of many weather variables, if done strictly by customary regression procedures would lead to considerable confusion because of some degree of multi-collinearity among the original or transformed weather variables. He also states that inclusion of groups of correlated variables in a regression model dilutes out some of the statistical significance of the coefficients. Furthermore, pronounced and misleading shifts in regression coefficients can occur depending on the patterns of correlation among independent variables.

Morris (1972) suggests a method for avoiding the problems which he has described. The method is to develop
indices which incorporate simple weather observations into a single number or small set of numbers which represents the cumulative influences of many factors on yields. Such indices, he says, can be obtained through the use of simulation models.

With simulation models, raw meteorological observations can be converted, by appropriate computations incorporating the proper physical and biological relationships as found from other studies, into indexes which integrate the contributions of weather to crop yields. Moisture stress indexes have been obtained from such models, with excellent results in many instances (Morris, 1972, p. 2).

Baier and Robertson (1968) found estimates of soil moisture to be more suitable than raw meteorological data for explaining the influence of weather on five seasons of wheat yields at eight Canadian locations. A soil-moisture balance program was used to estimate soil moisture during growth stages.

They concluded that the soil-moisture estimates obtained from their procedure produced a better relationship with yields than raw rainfall and temperature variables because the estimates were expressions of factors on which the crops were directly dependent.

Parks and Knetsch (1959) used total weighted drought days of each season as an independent variable in the analysis of mean corn yields obtained from five nitrogen-rate replications in an experiment conducted over a three-year
period in west Tennessee. They were able to account for most of the influence of weather in their analysis.

Sanderson (1954) states that crop forecasts using correlation techniques based on weather factors have been more successful in excessive climates than in moderate climates. This increased success in marginal climates as compared to results obtained under more nearly optimum conditions is generally due to the dominance of a single "limiting factor" such as moisture supply. For crops grown under nearly optimum conditions the variations in yield are less intensive, but less predictable, since they depend on a number of factors of approximately equal weight.

Watson (1963), in reviewing the work of Lawes and Gilbert (1880) on the Broadbalk wheat experiment in Rothamsted and the subsequent multiple-regression analysis of Fisher (1924) and Buck (1961), concludes that yields may be adequately described by a linear regression when one climatic factor, such as rainfall or lack of it, dominates over all others.

Hanks (1974), in a description of a model for predicting plant yield, shows a strong linear relationship between evapotranspiration and relative corn grain yield for both actual data and results predicted by a computer model.

Stewart et al. (1977), in a joint study with the University of California-Davis, Utah State University, Colorado
State University, and the University of Arizona on the effects of irrigation timing and salinity management on crop production, found that corn grain yields showed a very strong linear relationship to evapotranspiration with correlation coefficients ranging from 0.82 to 0.98. They found this strong linearity between grain yield and evapotranspiration to hold true at all of the testing sites and for all growth-stage irrigation treatments. They conclude that the modeling approach to yield prediction appears to be soundly based. The essential feature of a working model is, based on their findings, that evapotranspiration deficits below the maximum evapotranspiration for the season that maximizes yields reduce corn yields linearly.

Data of Mallett (1972) also showed yield reduction as a linear response. Mallett's work showed corn yields were reduced linearly as the number of days of moisture stress increased. Under very severe stress, he concludes, there could probably be some cumulative effects.

Barger and Thom (1949) developed a method for characterizing drought intensity in Iowa by looking at county rainfall records and corn yields. In this study they conclude that the correlation between maximum rainfall deficits and deviations of county corn yields from normal show that for years in which drought conditions occurred, from 25% to 60% of the total variation in yield was explained by rainfall deficits.
Corsi (1969), in reviewing the work of Dale (1964) and Dale and Shaw (1965) for corn, concludes that plant-water status was considered as the main factor responsible for the variation in yields. If this is true then regression equations using a measure of plant-water status to predict yields should be valid and give useful results.

Shaw (1978) gives a regression equation to predict corn yields from a weighted, moisture-stress index summed over an 85-day period surrounding silking. The regression equation assumes a top yield and subtracts off units of yield as units of moisture stress accumulate. The values of the base yield and the regression coefficient effectively determine the technology and management levels being used.

Other similar regression equations representing different technology and management levels are given in an earlier paper (Shaw, 1974). The results for 10 Iowa locations are combined and two regression equations are determined: one for high-yielding sites, and one for moderate-yielding sites. The correlations between the moisture-stress index and corn grain yields were -0.88 and -0.83, respectively.

In a study on the influence of spring soil moisture on seasonal moisture stress in Iowa, Zanzalari (1973) used a regression equation of the form $Y = 8616.8 - 135.3X$, where $Y$ is corn yield in kg/ha and $X$ is the seasonal stress index. This
is the same regression equation used by Shaw and Felch (1972) and Corsi (1969). This equation was found to have a correlation coefficient between the stress index and corn yield of -0.83 for most Iowa sites.

After making and examining adaptations and modifications in simulation-model-derived weather indexes for predicting Iowa corn yields, Morris (1972) computes a series of regression equations using data from 1,229 sites located in the seven Iowa counties used for weather index development. These equations showed that the indexes for moisture-stress conditions and excess moisture conditions, separately and in combination, significantly explained corn yield variations resulting from weather differences.

This review of literature has shown research which supports several concepts which are basic to the current study:

1. Seasonal water use by corn normally exceeds the amount of growing-season precipitation received in many areas (including Iowa).

2. Moisture from the high water-holding capacity soils of Iowa normally cannot alone support a growing corn crop through the season.

3. Moisture stress resulting from an imbalance between the amount of water furnished to the plant and the amount required by the plant will reduce corn yields.
4. Irrigation has been used in areas of the humid and subhumid United States (including Iowa) to effectively reduce moisture stress and increase yields.

5. Corn yields can be predicted relatively accurately using simulation water-balance models and linear regression of yield on weather event(s).
DATA AND PROCEDURES

Description of Sites

Nine sites were chosen for evaluation of irrigation effects on corn yields in Iowa. These nine sites represent eight of the nine Iowa crop reporting districts. The south-central district was not represented in an attempt to minimize computer costs. It was felt that irrigation potential would be very low in this area of the state, and probably the soil-moisture and meteorological conditions there were not much different from those in southeastern Iowa, which was represented.

The nine sites used represented the soil-moisture measuring sites used by Iowa State University. A brief description of each site is given below. The descriptions were taken from Zanzalari (1973). A more detailed description of most of these sites is given by Corsi (1969) and a thorough description of the soil types is found in Oschwald et al. (1965). The relative locations of the sites are shown in Figure 1.

Northwest

Doon - Northwest Iowa Research Center on Moody silt loam, well-drained.

Sutherland - the soil-moisture sampling site was
Figure 1. Location of soil-moisture sites
located near Primghar until 1957 when it was changed to the Northwest Iowa Research Center (Galva-Primghar) near Sutherland. The soil-moisture characteristics of the NMIRC's Galva silt loam were used in this work.

**North-central**

Kanawha - site locations for moisture sampling have been on the Northern Iowa Research Center near Kanawha. All sites have been on Webster silty clay loam.

**Northeast**

Elkader - actual moisture sampling site located six miles southeast of town on a well-drained Fayette silt loam. Rainfall data were taken from the town of Elkader.

**West-central**

Castana - Western Iowa Research Center on Ida silt loam, well-drained.

**Central**

Ames - Iowa State University Agronomy and Agricultural Engineering Research Center with Webster silty clay loam, poorly-drained. Although the actual soil-moisture sampling site was located at the
Beach Avenue fields in Colo silty clay loam in the years 1956-1964, the Webster soil field capacity was used for all years in this study.

East-central
Cedar Rapids - moisture sampling site is four miles south of the city in Klinger silt loam, somewhat poorly-drained. Rainfall data were from the airport weather station.

Southwest
Norwich-Shenandoah - soil samples were taken from the Norwich Soil Conservation Farm until 1966 when the site was changed to the Earl May Trial Gardens in Shenandoah. Both sites have Marshall silty clay loam.

Southeast
Burlington-Columbus Junction - early sampling was done at the Burlington Ordnance Plant on a Taintor silt loam. In 1968 the site was changed to five miles south of Columbus Junction, on a lighter, poorly-drained Mahaska silty clay loam. Rainfall data were recorded at Burlington and Columbus Junction.

Soil-moisture, pan evaporation, and rainfall data from these nine sites over the period from 1958 to 1977 were used
in the soil-moisture computer program described below to
calculate the water balance and moisture stress. A period
of twenty years was chosen so as not to include data which
would bias the results due to the approximately 22-year
drought cycle. Continuous data are available for most sta-
tions from 1954 to the present, but it was thought that in-
cluding the dry years of the 70's would be of more current
interest than including the dry years of the 50's.

Computer Program

Brief description

Calculations of the daily soil-moisture budget under
corn were made by the computer program described by Dale and
Hartley (1963) and modified by Morris (1972) and further re-
vised by the author. The following description of the gen-
eral nature of the program is taken from Dale (1964).

The water balance is determined between field capacity
and wilting. Incoming moisture is determined by subtracting
runoff from precipitation. Losses of moisture are determined
by adding evapotranspiration (ET) and percolation amounts.
Rainfall is allowed to bring the top layer to field capacity
and then moisture percolates to the next layer and so forth
through the profile. Evapotranspiration is adjusted for the
corn-root zone which changes with stage of development. If
moisture is insufficient, then ET is reduced from its maximum
value based upon the actual soil moisture present. Daily ET comes from daily evaporation-pan data and the stage of crop development. ET loss is subtracted from the soil profile before rainfall is added.

The soil-moisture program assumes a high level of farm management. This is consistent with what Rhoades and Nelson (1955) say about management under irrigation:

It does not pay to eliminate water as a limiting factor in corn production, or to improve the method of irrigating, and then have other factors limit yields. Most profitable returns from irrigated corn result only when all practices are geared for high production (p. 398).

Inputs

The inputs required by the soil-moisture program for computing the daily water balance between the soil moisture and water use by the plant, and for calculating the daily stress are:

1. Date of 75% silking.
2. Amount of plant-available water the soil can hold (hereafter referred to as field capacity, FC), recorded in inches for 6-inch layers from the surface to 5 feet.
3. Amount of starting plant-available soil moisture (hereafter referred to as initial soil-moisture profile, initial SMP), recorded in inches for 6-inch layers from the surface to 5 feet.
4. Daily precipitation amounts.
5. Daily pan evaporation values.

The date of 75% silking is used to adjust all moisture extraction procedures and water requirements of corn for stage of development. The silking dates were obtained from experimental plots where available and supplemented with data from the Iowa Crop and Livestock Reporting Service (Corsi, 1969).

The field capacity and initial soil-moisture profile values were obtained from data gathered as part of the Iowa soil-moisture survey. Gravimetric soil samples are taken in April and November to determine the moisture status of Iowa soils. The April value is used as the initial SMP value in this study.

The daily precipitation data came from rain gauges located at the experimental farms where soil-moisture samples were taken or, if no gauge was present, data from the nearest reporting source were used. In no case was a gauge more than a few miles from the sampling site (Zanzalari, 1973).

The daily pan evaporation values give an estimate of the atmospheric energy available for evapotranspiration. These are values of evaporation as occurring from a Weather Bureau Class A evaporation pan. Since evaporation data are not available for every location at which soil moisture is sampled, values for pan evaporation were taken from maps analyzed with isoevaporation lines. The isolines were drawn
from pan evaporation data from a few Iowa locations and some in neighboring states. Since evaporation is a conservative parameter, it is believed only small errors are involved by using values from isoevaporation lines drawn on daily pan evaporation maps (Corsi, 1969).

Other information which the program requires as input data are tables for runoff, ratio of evapotranspiration to open-pan evaporation as influenced by crop development, relative transpiration rate for different amounts of available soil moisture and atmospheric demand, and moisture extraction schedule. These data are not site or year dependent. Several changes were made in the data tables for relative transpiration rate (Tables 3 and 4 of the computer program). The most recent values were used (R. H. Shaw, Department of Agronomy, Iowa State University, Ames, Iowa, personal communication, 1978).

Modifications

Several modifications in the program were made in accordance with new methods of calculating the moisture balance, daily stress index and weighted stress index as described in Shaw (1978) and Shaw (1974):

1. Rooting is stimulated to greater depths under dry soil-moisture conditions in the spring. For years in which no percolation of water occurred from the 5-foot profile in
May and June, the program allowed corn to extract moisture from a 7-foot profile rather than just the 5-foot profile. The program assumed that all of the water from 5 to 7 feet became available to the plant at the same time; i.e., all of the moisture in the layer between 5 and 7 feet was put into the layer between 4.5 and 5 feet. Realistically, a gradual rooting-depth increase should be assumed, but the program was more easily modified by putting all of the subsoil moisture into the last layer, and only a minor error was believed to have been introduced. When the roots reached the 4.5- to 5-foot depth, all of the available moisture from 4.5 to 7 feet was assumed to be available. This was accomplished by adding a new set of field capacity and soil-moisture profile control cards which contained the appropriate field capacity and starting moisture values for the 4.5- to 7-foot depth in the 4.5- to 5-foot depth (the last 6-inch layer, layer 10) (Shaw, 1978).

2. The calculation of the daily stress index was modified to allow for a reduced stress if moisture were present in the surface layer of the soil due to recent rains. The daily stress index (RAWSTR) is now calculated in one of two ways depending on the values of pan evaporation (EVP), stressed evapotranspiration (STET), and evaporation from the surface six inches of soil (EVAP). If STET is greater than or equal to 0.04" and EVP is greater than 0.30", then
RAWSTR = 1 - STET/ET.

In all other cases the daily stress index is calculated as

\[
\text{RAWSTR} = 1 - \frac{\text{STET} + \text{EVAP}}{\text{ET}}
\]

where the maximum allowable value for EVAP is 0.05". (See Shaw, 1978, for more details.)

3. The period of time for which the seasonal stress index was calculated was expanded to 85 days made up of eight 5-day periods before and including the silking date and nine 5-day periods after the silking date. Weighting factors were given to each of the 5-day periods to account for the differential effects on yield due to the stage of development at which stress occurred. The weighting factors are given in Table 3. The daily values for each 5-day period are summed and the period index is multiplied by the appropriate weighting factor.

To account for the cumulative effects of severe stress an additional weighting factor of 1.5 was applied to the weighted stress indexes for those periods whose 5-day unweighted stress indexes were 4.5 or greater for two or more consecutive periods. Also, a weighting factor of 1.5 was applied to the weighted stress indexes for those periods of 1-before, 2-before, and 3-before whose 5-day unweighted stress indexes were 3.00 or greater. The sum of all of the weighted, 5-day values gives the seasonal weighted stress index for the
Table 3. Relative weighting factors used to evaluate the effect of stress on corn yield. Periods are 5-day periods relative to silking (after Shaw, 1974)

<table>
<thead>
<tr>
<th>Period</th>
<th>Weighting Factor</th>
<th>Period</th>
<th>Weighting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 before</td>
<td>0.50</td>
<td>1 after</td>
<td>2.00</td>
</tr>
<tr>
<td>7 before</td>
<td>0.50</td>
<td>2 after</td>
<td>1.30</td>
</tr>
<tr>
<td>6 before</td>
<td>1.00</td>
<td>3 after</td>
<td>1.30</td>
</tr>
<tr>
<td>5 before</td>
<td>1.00</td>
<td>4 after</td>
<td>1.30</td>
</tr>
<tr>
<td>4 before</td>
<td>1.00</td>
<td>5 after</td>
<td>1.30</td>
</tr>
<tr>
<td>3 before</td>
<td>1.00</td>
<td>6 after</td>
<td>1.30</td>
</tr>
<tr>
<td>2 before</td>
<td>1.75</td>
<td>7 after</td>
<td>1.20</td>
</tr>
<tr>
<td>1 before</td>
<td>2.00</td>
<td>8 after</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9 after</td>
<td>0.50</td>
</tr>
</tbody>
</table>

85-day period (Shaw, 1974).

In addition, whenever the unweighted stress indexes for periods 1-before and 1-after are 4.50 or greater, a crop failure is designated (R. H. Shaw, Department of Agronomy, Iowa State University, Ames, Iowa, personal communication, 1978).

Irrigation Simulation

A subroutine was written to simulate irrigation and was added to the soil-moisture program in order to determine the effects irrigation might have in reducing moisture stress in corn. A flow chart of the procedure used is given in Figure 2.
Figure 2. Flow chart of irrigation subroutine
Call from M/Prog

Is Day of Cycle Before 3rd?

Yes  Increment Day of Cycle

No  Determine Field Capacity for the Active Root Zone

Determine Soil-Moisture Profile for the Active Root Zone

Determine Amount of Irrigation Water to Apply to Bring SMP to 90% of FC

Amount Needed to be Applied Less than 1"?

Yes  Shut off System

No  Apply 1" of Water by Taking Successive Layers from the Surface to Field Capacity Until the Amount to Apply is Used up

Increment Total Amount of Irrigation Water Applied for the Season

Signal Antecedent Precipitation Index that the Water has been Added

Set Day of Cycle to 1

Calculate % Available Moisture in the Active Root Zone and the Top

Signal that the System is ON
This subroutine simulates irrigation of a point in a large corn field (approximately 160 acres) on a high waterholding capacity soil in Iowa. The field is irrigated with a center-pivot sprinkler irrigation system which 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 (S. W. Melvin, Agricultural Engineering, Iowa State University, Ames, Iowa, personal communication, 1978).

Irrigation was begun after June 30 whenever the soilmoisture 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 usually small and irrigation probably was not needed in the spring. Also, commencement of irrigation after June 30 avoided a potential wetness problem due to spring rains added on top of irrigation.

Two field capacity criteria were used as requirements for scheduling irrigation:

1. The system was turned on when the available moisture in the active root zone fell to less than or equal to 75% of the field capacity value for the active root zone. This was supposed to represent the irrigation procedure of a farmer using a high level of irrigation management. Hereafter this requirement will be referred to as the "75% criterion."
2. The system was turned on when the available moisture in the active root zone fell to less than or equal to 50% of the field capacity value for the active root zone. This was supposed to represent the irrigation procedure of a farmer using a lower level of management. Hereafter this requirement will be referred to as the "50% criterion."

After the requirement for irrigation has been met and the system is turned on, then irrigation continues until the available moisture in the active root zone has been brought up to 90% of the field capacity value for the active root zone. To avoid the potential wetness problem that could result if one inch of irrigation water were applied when the moisture status of the active root zone was just below 90% of field capacity, irrigation was discontinued when the available moisture in the active root zone was brought up to within one inch of 90% of the field capacity value for the active root zone. The reason for irrigation to "within one inch" of the field capacity value for the active root zone was to simulate how water might realistically be applied by an irrigation system. Although it is possible with computer simulation to apply the exact amount of water needed to bring the active root zone to 90% of field capacity, this is not what realistically would be done. A real operator would probably not readjust his sprinkler system to apply just enough water to bring the profile to 90% of field
capacity (S. W. Melvin, Agricultural Engineering, Iowa State University, Ames, Iowa, personal communication, 1978).

Irrigation was used anytime when the soil-moisture profile indicated a need according to the above criteria from July 1 (calendar date) to September 30 (date adjusted for silking). Using an ending date adjusted for silking corresponds well to the needs of the plant, but the main reason for using this ending date was convenience with the soil-moisture program. After September 30 adjusted for silking, the program switches to a different segment to calculate the moisture balance.

Frequency distributions of the annual amounts of irrigation water applied were drawn for the two irrigation criteria.

Moisture Stress - Yield Relationship

Calculations of yearly corn yields (Y, kg/ha) for each site were made using values of the 85-day weighted stress index (X) in the equation:

\[ Y = 9682 - 118.6X \]

as given by Shaw (1978).

From these calculated data, frequency distributions of unirrigated corn yields as well as corn yields for the two irrigation scheduling criteria were drawn. Frequency
distributions of the yield increases due to irrigation were also drawn.

Percolation

The monthly percolation totals for each station for July, August, and September were calculated for each year for the unirrigated and the two irrigated situations. The 3-month totals were used to give a rough, somewhat general idea about the potential for irrigation to cause a wetness problem during the growing season.

There may seem to be some inconsistency in the definition of percolation since we determine percolation as the water which flows out of the soil profile, and we have used two different profiles (5-foot and 7-foot) depending on the spring conditions. Actually this inconsistency is probably not as bad as it first appears. In a dry-spring year the subsoil moisture is probably depleted more than normal. It therefore seems logical that it should take more moisture to bring the profile back to field capacity and cause saturation. Also, by late July and August of a dry-spring year the root system of the corn plant has developed into and is extracting moisture from layers below five feet. Since moisture is being extracted below five feet, it takes more water to saturate the profile. So the double definition of percolation which depends on the spring conditions really does
give a valid index of when excess moisture has occurred.

It may have been better to use a 3-month total including October rather than July to see how the profile charged by irrigation reacted in terms of increased percolation when the fall rains began, but in some years our data only went to September 30.

Frequency distributions were drawn for the 3-month percolation totals for the unirrigated and two irrigated cases for each station.

Preseason Irrigation

The effects of preseason irrigation were looked at to evaluate effects of such a practice on seasonal irrigation amounts and removal of moisture stress which occurs prior to the beginning of regular season irrigation on July 1.

The program looks at the field capacity and initial soil-moisture profile values (5-foot profile) given at the beginning of a year's data. It then calculates how much water should be added to bring the profile to 80% of field capacity. This amount of water is then added to the profile starting with the top layer, filling it to field capacity, moving to the next layer, filling it to field capacity, and so on until no more water is available to add. This method has the effect of pushing the top layers to field capacity while the moisture content of the lower layers is less than
field capacity.

The program does not specify how or when this preseason irrigation is applied (i.e., spring or fall); it only assumes that somehow, sometime, it does get put on and that by doing so the spring soil moisture has been increased.

An initial attempt was made to use the regular irrigation subroutine to apply the preseason irrigation starting at a uniform date, April 20. This seemed to be the earliest common date of record for all years used in this study. The problem arose that many times this method prolonged irrigation into middle and late May, which would interfere with seedbed preparation and planting operations. This suggests that perhaps most preseason irrigation would have to be done in the fall after harvest.

Not all of the nine stations' 20 years of data were re-run with preseason irrigation. Only those years were run where the initial soil-moisture profiles were less than or equal to 40% of field capacity (5-foot profile). This criterion was picked because it was thought that those years would show the conditions in which stress occurred before July 1. The initial reason for preseason irrigation was primarily to remove this early season stress.

A second criterion was used for the western stations (i.e., Doon, Sutherland, Castana, and Norwich-Shenandoah). At those stations years were also picked when the initial
soil-moisture profiles were less than or equal to 70% of field capacity (5-foot profile). The logic for using two criteria for these stations is that the western part of the state is generally drier than the eastern part. Thus, preseason irrigation under this second, less-dry criterion should cause fewer excess moisture problems in the spring than if it were used on the eastern stations. Also, as will be shown later, more irrigation water is applied during the regular irrigation season in western Iowa and preseason irrigation should have the effect of lowering the amount of irrigation water needed during this time period. After preseason irrigation, regular season irrigation was scheduled according to the 50% criterion. Table 4 gives the number of years out of 20 selected for preseason irrigation for each of the nine stations used in the study.
Table 4. Number of years out of 20 selected for preseason irrigation, by station

<table>
<thead>
<tr>
<th>Station</th>
<th>Number of years out of 20 when spring soil-moisture profile is less than or equal to ...</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40% of field capacity</td>
</tr>
<tr>
<td>Doon</td>
<td>5</td>
</tr>
<tr>
<td>Sutherland</td>
<td>4</td>
</tr>
<tr>
<td>Ames</td>
<td>2</td>
</tr>
<tr>
<td>Burlington</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Columbus Junction</td>
</tr>
<tr>
<td>Castana</td>
<td>2</td>
</tr>
<tr>
<td>Cedar Rapids</td>
<td>0</td>
</tr>
<tr>
<td>Elkader</td>
<td>0</td>
</tr>
<tr>
<td>Kanawha</td>
<td>0</td>
</tr>
<tr>
<td>Norwich-Shenandoah</td>
<td>1</td>
</tr>
</tbody>
</table>

<sup>a</sup>Numbers in parentheses are for comparison only. These stations did not have years selected for preseason irrigation under this criterion.
RESULTS AND DISCUSSION

Frequency Distributions of Unirrigated Corn Yields

As was stated in the literature review, corn yields in Iowa are reduced by moisture stress. This reduction in yield due to moisture stress is present to some degree almost every year at all Iowa locations. For most years at most Iowa locations where corn is grown this reduction in yield is not severe. The histograms of unirrigated corn yields (Figures 3-11) serve as a base for determining the effects of irrigation on corn yields. They also help to point out those locations which have the more severe moisture stresses occurring in more years, thereby showing areas of the state which offer the most potential benefit for reducing moisture stress by irrigation.

Doon: The distribution of unirrigated corn yields for Doon (Figure 3) shows that in 9 out of 20 years yields are not severely reduced and fall within the range of 7750–9750 kg/ha (124–155 bu/acre). In the remaining 11 years the yields are more severely restricted by moisture stress. Six of these years have an average yield of 6013 kg/ha (96 bu/acre), 4 years have an average yield of 3195 kg/ha (49 bu/acre) and 1 year shows the occurrence of a total crop failure. The mean unirrigated yield for the 20-year period was 6389 kg/ha (102 bu/acre).
Figure 3. Distributions of corn yields for Doon, Iowa, 1958-1977
Sutherland: The distribution of unirrigated corn yields for Sutherland (Figure 4) shows that in 12 out of 20 years yields were not severely reduced and fell within a range of 7750-9750 kg/ha (124-155 bu/acre). In the remaining 8 years the yields were more severely restricted by moisture stress with the average yield for these 8 years being 5136 kg/ha (82 bu/acre). The average unirrigated yield for the 20-year period was 7465 kg/ha (119 bu/acre).

Ames: The distribution of unirrigated corn yields for Ames (Figure 5) shows that 11 out of 20 years had an average yield of 9334 kg/ha (149 bu/acre). Seven out of 20 years had an average yield of 7710 kg/ha (123 bu/acre). The remaining 2 years had severely reduced yields of 4944 kg/ha (79 bu/acre) and 3415 kg/ha (54 bu/acre). The average unirrigated yield for the 20-year period was 8250 kg/ha (131 bu/acre).

Burlington-Columbus Junction: The distribution of unirrigated corn yields for Burlington-Columbus Junction (Figure 6) shows that 18 out of 20 years had yields in the range of 8250-9750 kg/ha (131-155 bu/acre). The remaining 2 years had an average yield of 7408 kg/ha (118 bu/acre). The average unirrigated yield for the 20-year period was 9259 kg/ha (147 bu/acre).

Castana: The distribution of unirrigated corn yields for Castana (Figure 7) shows that 11 out of 20 years had yields which fell in the range of 8750-9750 kg/ha (139-155


Figure 4. Distributions of corn yields for Sutherland, Iowa, 1958-1977
Figure 5. Distributions of corn yields for Ames, Iowa, 1958-1977
Figure 6. Distributions of corn yields for Burlington-Columbus Junction, Iowa 1958-1977
Figure 7. Distributions of corn yields for Castana, Iowa, 1958-1977
bu/acre). Seven out of 20 years had yields which fell in the range of 5750-7750 kg/ha (92-123 bu/acre). The average unirrigated yield for the 20-year period was 7925 kg/ha (126 bu/acre).

Cedar Rapids: The distribution of unirrigated corn yields for Cedar Rapids (Figure 8) shows that 18 out of 20 years had yields which fell in the range of 8250-9750 kg/ha (131-155 bu/acre). The remaining 2 years had an average yield of 7505 kg/ha (120 bu/acre). The average unirrigated yield for the 20-year period was 9250 kg/ha (147 bu/acre).

Elkader: The distribution of unirrigated corn yields for Elkader (Figure 9) shows that 16 out of 20 years had yields in the range of 8250-9750 kg/ha (131-155 bu/acre). Three years had an average yield of 7919 kg/ha (126 bu/acre) and 1 year had a yield of 6263 kg/ha (100 bu/acre). The average unirrigated yield for the 20-year period was 8944 kg/ha (142 bu/acre).

Kanawha: The distribution of unirrigated corn yields for Kanawha (Figure 10) shows that 13 out of 20 years had yields in the range of 8250-9750 kg/ha (131-155 bu/acre). Six years out of 20 had yields in the range of 6750-8250 kg/ha (108-131 bu/acre). One year out of 20 had a yield of 5813 kg/ha (93 bu/acre). The average unirrigated yield for the 20-year period was 8628 kg/ha (137 bu/acre).
Figure 8. Distributions of corn yields for Cedar Rapids, Iowa, 1958-1977
Figure 9. Distributions of corn yields for Elkader, Iowa, 1958-1977
Figure 10. Distributions of corn yields for Kanawha, Iowa, 1958-1977
Norwich-Shenandoah: The distribution of unirrigated corn yields for Norwich-Shenandoah (Figure 11) shows that 12 out of 20 years had yields in the range of 8250-9750 kg/ha (131-155 bu/acre). Six years out of 20 had yields in the range of 6250-8250 kg/ha (100-116 bu/acre). The remaining 2 years had an average yield of 4678 kg/ha (75 bu/acre). The average unirrigated yield for the 20-year period was 8215 kg/ha (131 bu/acre).

At all stations except Doon the unirrigated corn yields for at least 50% of the years under consideration fell into the top three classes, 8250-9750 kg/ha (131-155 bu/acre). This is not a surprising result for it is fairly well-known that most of Iowa is a good place to grow corn. But from the histograms of unirrigated yields it can be clearly seen that moisture stress reduces yields many years in Iowa, and at some locations this stress causes severe reductions and occurs more frequently than at other locations.

For most of the stations in this study the distributions of unirrigated corn yields are bimodal; that is, most of the yields for a given station fall around one of two mean values. This is particularly noticeable at Doon, Sutherland, Ames, Castana, and Norwich-Shenandoah. It is the secondary, lower-yield cluster of years which suggests that irrigation may be useful in Iowa. For many Iowa locations a large percentage of years have yields which are substantially reduced due to
Figure 11. Distributions of corn yields for Norwich-Shenandoah, Iowa, 1958-1977.
moisture stress and could be helped out by irrigation. For example, at Doon, Sutherland, Castana, and Norwich-Shenandoah 47% of the years have yields which are reduced by 2182-5128 kg/ha (35-83 bu/acre) due to moisture stress. In addition, another 12% of the years at these locations have yields which are reduced to an even greater extent.

But it is not just the western Iowa stations which show yields reduced by moisture stress which could be removed by irrigation, although the amount of yield reduction is less and the number of years moisture stress occurs is fewer at these locations than western Iowa. For 23% of the years at Ames, Burlington-Columbus Junction, Cedar Rapids, Elkader, and Kanawha the yields are reduced by at least 1432 kg/ha (23 bu/acre), and at times are reduced by as much as 6267 kg/ha (100 bu/acre).

An easily detectable yield loss of 628 kg/ha (10 bu/acre) due to moisture stress can be seen in 23% of the years at Burlington-Columbus Junction and Cedar Rapids, 49% of the years at Ames, Castana, Elkader, Kanawha, and Norwich-Shenandoah, and 75% of the years at Doon and Sutherland.

The major point to be made here is that there are many years when corn yields are reduced by moisture stress. Most of the really large yield reductions occur in western Iowa, but moderate reductions in yields are also seen across the rest of Iowa. Although the highest frequency of years with
yields reduced by moisture stress occurs in western Iowa, other parts of the state do have a substantial proportion of their years which have lower than optimum yields due to moisture stress.

Frequency Distributions of Irrigated Corn Yields and Yield Increases Due to Irrigation

The results of irrigation under the two scheduling criteria described previously are given in Figures 3-20 in the form of histograms of irrigated yields and yield increases due to irrigation. The results are briefly described for each station. Frequency distributions for irrigated yields and yield increases due to irrigation are given for each station under both the 75% and 50% criteria of scheduling irrigation. But the differences between the results obtained under the two criteria were not found to be statistically significant, so only the mean values between the two criteria are given in the discussion which follows.

Doon: The distributions of irrigated yields at Doon for the two scheduling criteria are given in Figure 3. The distributions of yield increases at Doon due to irrigation are given in Figure 12. With irrigation, yields for all 20 years fell in the range of 8750-9750 kg/ha (140-155 bu/acre). The mean irrigated yield was 9636 kg/ha (153 bu/acre). The mean yield increase due to irrigation was 3247 kg/ha (52
Figure 12. Distributions of yield increases due to irrigation at Doon, Iowa, 1958-1977
YIELD INCREASE DUE TO IRRIGATION (kg/ha x 100)
bu/acre). The yield increases ranged from 52-9682 kg/ha (1-154 bu/acre).

Sutherland: The distributions of irrigated yields at Sutherland for the two scheduling criteria are given in Figure 4. The distributions of yield increases at Sutherland due to irrigation are given in Figure 13. With irrigation, yields for all 20 years fell in the range of 9250-9750 kg/ha (147-155 bu/acre). The mean irrigated yield was 9665 kg/ha (154 bu/acre). The mean yield increase due to irrigation was 2200 kg/ha (35 bu/acre). The yield increases ranged from 29-6818 kg/ha (0-109 bu/acre).

Ames: The distributions of irrigated yields at Ames are given in Figure 5. The distributions of yield increases at Ames due to irrigation are given in Figure 14. With irrigation, yields for 19 out of 20 years fell in the range of 9250-9750 kg/ha (147-155 bu/acre). One year out of 20 had an irrigated yield of 7607 kg/ha (122 bu/acre). The mean irrigated yield was 9561 kg/ha (152 bu/acre). The mean yield increase due to irrigation was 1311 kg/ha (21 bu/acre). The yield increases ranged from 6-4738 kg/ha (0-75 bu/acre).

Burlington-Columbus Junction: The distributions of irrigated yields at Burlington-Columbus Junction are given in Figure 6. The distributions of yield increases for this location are given in Figure 15. With irrigation, yields for all 20 years fell in the range of 9250-9750 kg/ha (147-155
Figure 13. Distributions of yield increases due to irrigation at Sutherland, Iowa, 1958-1977
SUTHERLAND

50% Criterion

YIELD INCREASE DUE TO IRRIGATION (kg/ha x 100)

75% Criterion
Figure 14. Distributions of yield increases due to irrigation at Ames, Iowa, 1958-1977
YIELD INCREASE DUE TO IRRIGATION (kg/ha x 100)
Figure 15. Distributions of yield increases due to irrigation at Burlington-Columbus Junction, Iowa, 1958-1977
YIELD INCREASE DUE TO IRRIGATION (kg/ha x 100)
bu/acre). The mean irrigated yield was 9676 kg/ha (154 bu/acre). The mean yield increase due to irrigation was 417 kg/ha (7 bu/acre). The yield increases ranged from 0-2552 kg/ha (0-41 bu/acre).

Castana: The distributions of irrigated yields at Castana are given in Figure 7. The distributions of yield increases due to irrigation are given in Figure 16. With irrigation, yields for 20 out of 20 years fell in the range of 9204-9750 kg/ha (147-155 bu/acre). The mean irrigated yield was 9641 kg/ha (154 bu/acre). The mean yield increase due to irrigation was 1716 kg/ha (27 bu/acre). The yield increases ranged from 10-6506 kg/ha (0-104 bu/acre).

Cedar Rapids: The distributions of irrigated yields are given in Figure 8. The distributions of yield increases due to irrigation are given in Figure 17. With irrigation, yields for 20 out of 20 years fell in the range of 9250-9750 kg/ha (147-155 bu/acre). The mean irrigated yield was 9666 kg/ha (154 bu/acre). The mean yield increase due to irrigation was 416 kg/ha (7 bu/acre). The yield increases ranged from 0-2252 kg/ha (0-36 bu/acre).

Elkader: The distributions of irrigated yields at Elkader are given in Figure 9. The distributions of yield increases due to irrigation are given in Figure 18. With irrigation, yields for 20 out of 20 years fell in the range of 9240-9750 kg/ha (147-155 bu/acre). The mean irrigated
Figure 16. Distributions of yield increases due to irrigation at Castana, Iowa, 1958-1977
YIELD INCREASE DUE TO IRRIGATION (kg/ha x 100)
Figure 17. Distributions of yield increases due to irrigation at Cedar Rapids, Iowa, 1958-1977
CEDAR RAPIDS

50% Criterion

75% Criterion

YIELD INCREASE DUE TO IRRIGATION (kg/ha x 100)
Figure 18. Distributions of yield increases due to irrigation at Elkader, Iowa, 1958-1977
ELKADER

50% Criterion

75% Criterion

YIELD INCREASE DUE TO IRRIGATION (kg/ha x 100)
yield was 9648 kg/ha (154 bu/acre). The mean yield increase due to irrigation was 704 kg/ha (11 bu/acre). The yield increases ranged from 0-3419 kg/ha (0-54 bu/acre).

Kanawha: The distributions of irrigated yields at Kanawha are given in Figure 10. The distributions of yield increases due to irrigation are given in Figure 19. With irrigation, yields for 20 out of 20 years fell in the range of 9250-9750 kg/ha (147-155 bu/acre). The mean irrigated yield was 9671 kg/ha (154 bu/acre). The mean yield increase due to irrigation was 1043 kg/ha (17 bu/acre). The yield increases ranged from 0-3864 kg/ha (0-62 bu/acre).

Norwich-Shenandoah: The distributions of irrigated yields at Norwich-Shenandoah are given in Figure 11. The distributions of yield increases due to irrigation are given in Figure 20. With irrigation, yields for 18 out of 20 years fell in the range of 9250-9750 kg/ha (147-155 bu/acre). One year out of 20 had an irrigated yield of 9007 kg/ha (144 bu/acre) and one year out of 20 had an irrigated yield of 8661 kg/ha (138 bu/acre). The mean irrigated yield was 9577 kg/ha (153 bu/acre). The mean yield increase due to irrigation was 1362 kg/ha (22 bu/acre). The yield increases ranged from 0-4220 kg/ha (0-67 bu/acre).

It can be seen from the distributions of irrigated yields that when irrigation is used, yield reductions due to moisture stress are, in most cases, very small. In fact, in most
Figure 19. Distributions of yield increases due to irrigation at Kanawha, Iowa, 1958-1977
YIELD INCREASE DUE TO IRRIGATION (kg/ha x 100)
Figure 20. Distributions of yield increases due to irrigation at Norwich-Shenandoah, Iowa, 1958-1977
NORWICH-SHENANDOAH

50% Criterion

75% Criterion

YIELD INCREASE DUE TO IRRIGATION (kg/ha x 100)
situations if there is a yield reduction present it is less than 628 kg/ha (10 bu/acre). The irrigated yield amounts are fairly uniform across the state, indicating that irrigation can be effectively used in most parts of the state on high water-holding capacity soils to increase yields by decreasing moisture stress.

The most dramatic yield increases due to irrigation occurred at Doon and Sutherland where the average yield increases were greater than 2197 kg/ha (35 bu/acre). The comparatively flat distributions of yield increases at these two stations show the broad range of values obtainable due to the variable moisture conditions in northwest Iowa. At Ames, Kanawha, Castana, and Norwich-Shenandoah the yield increases are not as great as in northwest Iowa. The average yield increases at these stations are between 1067 and 1570 kg/ha (17 and 25 bu/acre). The distributions of yield increases fail to show any yield increases above 6750 kg/ha (108 bu/acre), and the distributions are skewed, favoring the yield increases in the range 0-1250 kg/ha (0-29 bu/acre). At Burlington-Columbus Junction, Cedar Rapids, and Elkader, the yield increases are still smaller, the averages being between 408 and 753 kg/ha (7 and 12 bu/acre). The frequency distributions of yield increases for these stations are even more heavily skewed towards the lower yield increases, with a very pronounced peak occurring in the class with a class mark of
0 kg/ha. The results are due to the less variable moisture situation at these stations than at the other Iowa locations studied. Also the maximum yield increases due to irrigation are less than at other Iowa locations because of the lower degree to which moisture stress occurs in eastern Iowa in most years.

In all cases, if there was a difference in the yields obtained from the two irrigation scheduling criteria, the yields were greater under the 75% criterion. But, as mentioned previously, the differences between the yield results obtained from the two scheduling criteria were nonsignificant. This says that there is no particular yield advantage to using the higher level of irrigation management (the 75% criterion) to reduce moisture stress and increase yields.

There were a few situations in which moisture stress did occur after July 1 even with irrigation. These situations arose when the soil-moisture profile was severely depleted in the spring and even continuous irrigation beginning on July 1 could not recharge the profile to a point where no stress would occur. The demand for moisture was too great to be satisfied by just one inch of water every three days. But this stress was usually quite small and caused only a minor yield reduction.

A more serious moisture problem and resultant yield reduction arises in response to stress which occurs prior to
when the irrigation system first gets a chance to work on July 1. The problem is due to insufficient recharging of the soil-moisture profile by fall and spring rains and snow melt. This problem occurs in 16% of the years studied and in many cases is not severe. The average pre-July stress was 1.5 units, causing an average yield reduction of 176 kg/ha (3 bu/acre). An attempt to remove or reduce this stress with preseason irrigation was done and will be described later in another section.

Amount of Irrigation Water Applied

The amount of irrigation water applied per irrigation season was influenced by the amount of soil moisture available to the plant, the amount of rainfall during the growing season, and the atmospheric demand for moisture. As expected, the amount of water applied varied greatly from year to year. The greatest amounts were applied in northwest Iowa and the least amounts were applied in east and southeast Iowa. The following is a brief description of the irrigation water application amounts.

Doon: The distributions of irrigation amounts are given in Figure 21 for the two scheduling criteria. With the 50% criterion an average of 9.65 inches/year was applied; the range was 4-19 inches/year. With the 75% criterion an average of 10.50 inches/year was applied; the range was 4-19
Figure 21. Distributions of seasonal irrigation application amounts at Doon, Iowa, 1958-1977
50% Criterion

75% Criterion

INCHES APPLIED/YEAR

DOON

# OF YEARS

10 5 10 5

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19

# OF YEARS

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
inches/year.

Sutherland: The distributions of irrigation amounts are given in Figure 22 for the two scheduling criteria. With the 50% criterion an average of 7.55 inches/year was applied; the range was 0-16 inches/year. With the 75% criterion an average of 9.60 inches/year was applied; the range was 3-18 inches/year.

Ames: The distributions of irrigation amounts are given in Figure 23 for the two scheduling criteria. With the 50% criterion an average of 5.35 inches/year was applied; the range was 0-15 inches/year. With the 75% criterion an average of 7.05 inches/year was applied; the range was 2-15 inches/year.

Burlington-Columbus Junction: The distributions of irrigation amounts are given in Figure 24 for the two scheduling criteria. With the 50% criterion an average of 3.70 inches/year was applied; the range was 0-11 inches/year. With the 75% criterion an average of 5.00 inches/year was applied; the range was 0-10 inches/year.

Castana: The distributions of irrigation amounts are given in Figure 25 for the two scheduling criteria. With the 50% criterion an average of 6.85 inches/year was applied; the range was 1-19 inches/year. With the 75% criterion an average of 7.85 inches/year was applied; the range was 3-19 inches/year.
Figure 22. Distributions of seasonal irrigation application amounts at Sutherland, Iowa, 1958-1977
Figure 23. Distributions of seasonal irrigation application amounts at Ames, Iowa, 1958-1977.
Figure 24. Distributions at seasonal irrigation application amounts at Burlington-Columbus Junction, Iowa, 1958-1977.
Figure 25. Distributions of seasonal irrigation application amounts at Castana, Iowa, 1958-1977.
Cedar Rapids: The distributions of irrigation amounts are given in Figure 26. With the 50% criterion an average of 3.05 inches/year was applied; the range was 0-8 inches/year. With the 75% criterion an average of 4.60 inches/year was applied; the range was 1-9 inches/year.

Elkader: The distributions of irrigation amounts are given in Figure 27. With the 50% criterion an average of 4.25 inches/year was applied; the range was 0-13 inches/year. With the 75% criterion an average of 5.55 inches/year was applied; the range was 0-13 inches/year.

Kanawha: The distributions of irrigation amounts are given in Figure 28. With the 50% criterion an average of 5.10 inches/year was applied; the range was 0-13 inches/year. With the 75% criterion an average of 6.70 inches/year was applied; the range was 2-16 inches/year.

Norwich-Shenandoah: The distributions of irrigation amounts are given in Figure 29. With the 50% criterion an average of 5.55 inches/year was applied; the range was 0-13 inches/year. With the 75% criterion an average of 7.10 inches/year was applied; the range was 1-14 inches/year.

In all cases the data show that the average amount of seasonal irrigation water applied was greater when using the 75% criterion than when using the 50% criterion. But only at Cedar Rapids was this difference statistically significant. This was probably due to the fact that of the nine stations
Figure 26. Distributions of seasonal irrigation application amounts at Cedar Rapids, Iowa, 1958-1977.
Figure 27. Distributions of seasonal irrigation application amounts at Elkader, Iowa, 1958-1977
Figure 28. Distributions of seasonal irrigation application amounts at Kanawha, Iowa, 1958-1977
Figure 29. Distributions of seasonal irrigation application amounts at Norwich-Shenandoah, Iowa, 1958-1977.
studied, Cedar Rapids had the lowest range of values of application amounts.

The wide range of values is probably the most striking feature of the distributions of irrigation amounts. The range of values is greatest at Doon, Sutherland, Castana, and Ames, and probably due to the more variable moisture conditions during the growing season here than at locations such as Cedar Rapids and Burlington-Columbus Junction, which had the smallest range of values.

When using the 75% criterion, irrigation is used to some extent in 99% of the years. But when the 50% criterion is used, irrigation is used in only 81% of the years. This is a fairly major reduction in the number of years that irrigation was required. This result, combined with the results previously discussed (i.e., no significant yield differences between the two irrigation scheduling criteria, and the trend seen for reduced application amounts of irrigation water under the 50% criterion as compared to the 75% criterion, which would reduce the potential for having a wetness problem in the fall) provides a fairly strong argument for scheduling irrigation by the 50% criterion. The average seasonal application amounts are given in Table 5.
Table 5. Average seasonal applications of irrigation water (inches)

<table>
<thead>
<tr>
<th>Station</th>
<th>50%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doon</td>
<td>9.65</td>
<td>10.50</td>
</tr>
<tr>
<td>Sutherland</td>
<td>7.55</td>
<td>9.60</td>
</tr>
<tr>
<td>Ames</td>
<td>5.35</td>
<td>7.05</td>
</tr>
<tr>
<td>Burlington-Columbus Junction</td>
<td>3.70</td>
<td>5.00</td>
</tr>
<tr>
<td>Castana</td>
<td>6.85</td>
<td>7.85</td>
</tr>
<tr>
<td>Cedar Rapids</td>
<td>3.05</td>
<td>4.60</td>
</tr>
<tr>
<td>Elkader</td>
<td>4.25</td>
<td>5.55</td>
</tr>
<tr>
<td>Kanawha</td>
<td>5.10</td>
<td>6.70</td>
</tr>
<tr>
<td>Norwich-Shenandoah</td>
<td>5.55</td>
<td>7.10</td>
</tr>
</tbody>
</table>

Frequency Distributions of July, August, and September Percolation Totals

The frequency distributions of combined July, August, and September percolation for the unirrigated and the two irrigated situations are given by station in Figures 30-38.

The sums of July, August, and September percolation amounts provide somewhat rough indications of times when excess moisture may cause problems or potential yield reductions. All of the classes in the frequency distributions
Figure 30. Distributions of combined July, August, and September percolation at Doon, Iowa, 1958-1977
DOON

75% Criterion

50% Criterion

Unirrigated

INCHES OF PERCOLATION

# OF YEARS
Figure 31. Distributions of combined July, August, and September percolation at Sutherland, Iowa, 1958-1977.
Figure 32. Distributions of combined July, August, and September percolation at Ames, Iowa, 1958–1977.
Figure 33. Distributions of combined July, August, and September percolation at Burlington-Columbus Junction, Iowa, 1958-1977.
BURLEON-COLUMBUS JUNCTION

Unirrigated

50% Criterion

75% Criterion

INCHES OF PERCOLATION

# OF YEARS

0 0.25 1.25 2.25 3.25 4.25 ≥5.00

0 0.25 1.25 2.25 3.25 4.25 ≥5.00

0 0.25 1.25 2.25 3.25 4.25 ≥5.00
Figure 34. Distributions of combined July, August, and September percolation at Castana, Iowa, 1958-1977.
Figure 35. Distributions of combined July, August, and September percolation at Cedar Rapids, Iowa, 1958-1977.
Figure 36. Distributions of combined July, August, and September percolation at Elkader, Iowa, 1958-1977
Figure 37. Distributions of combined July, August, and September percolation at Kanawha, Iowa, 1958-1977
Figure 38. Distributions of combined July, August, and September percolation at Norwich-Shenandoah, Iowa, 1958-1977.
are 0.5 inches of percolation water in size except the first class. The first class is comprised of all years in which percolation did not occur. This class has, in all cases at every station, the highest frequency.

It is probably fair to assume that in years in which no percolation occurs in July, August, and September there are probably no adverse excess moisture effects during the summer. This probably holds true for years in which the 3-month percolation sum is less than or equal to an inch. The cases when this amount of percolation could indicate a problem are in years when most or all of the percolation comes at the end of September followed by large precipitation amounts in October. This could create a wetness problem which would hinder harvest. Table 6 shows the number of years out of 20 which had 3-month percolation totals greater than one inch and at least 80% of the total occurring in September.

September percolation data for Doon, Cedar Rapids, Elkader, Kanawha, and Norwich-Shenandoah were not available for 1977. September precipitation data for these stations were compared with previous years' September precipitation and percolation values to roughly determine the missing percolation values for 1977. The values reported in Table 6 reflect this fact so that all values represent number of years out of 20.

When the values in Table 6 are averaged for all nine
Table 6. Number of years out of 20 with 3-month percolation totals greater than one inch and at least 80% of the total occurring in September

<table>
<thead>
<tr>
<th>Station</th>
<th>Unirrigated</th>
<th>50% criterion</th>
<th>75% criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doon</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Sutherland</td>
<td>0</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Ames</td>
<td>0</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Burlington-Columbus Junction</td>
<td>4</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Castana</td>
<td>0</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Cedar Rapids</td>
<td>3</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Elkader</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Kanawha</td>
<td>1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Norwich-Shenandoah</td>
<td>1</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

stations, it is seen that when irrigation is not used a wetness problem would probably occur only 6% of the time. But if irrigation is used the wetness potential increases to 23% of the time for the 50% criterion and 30% of the time for the 75% criterion. The frequency of a wetness problem is higher in the eastern and southeastern parts of Iowa, and lower in the northwestern part of the state. At all nine stations the frequency of a wetness problem is higher under the 50% criterion than for the unirrigated case, and it is higher
under the 75% criterion than under the 50% criterion.

Irrigation under the 50% criterion produces a statistically significant increase in the amount of percolation as compared with the amount of percolation from unirrigated years at Doon, Ames, and Castana. The 75% criterion significantly increases the amount of percolation as compared with the amount of percolation from unirrigated years at Doon, Sutherland, Ames, and Castana. The difference between percolation amounts under the 50% criterion and the 75% criterion is not significant at any station (see Table 7).

Irrigation by Charging the Entire Profile as Compared to Charging the Active Root Zone

As described in a previous section, irrigation was accomplished by adding water until the percent available moisture in the active root zone was brought to within one inch of 90% of the field capacity value in the active root zone. Most recommendations for irrigation suggest that a better way to irrigate is to continue irrigation until the entire profile (not just the active root zone) is charged with water. The reason for the preference of this method of irrigation is that it avoids the possible formation of dry layers in the soil profile. Roots cannot grow into or function in dry layers.

The main problem with only irrigating the active root
Table 7. 3-month percolation means and differences (inches)

<table>
<thead>
<tr>
<th>Station</th>
<th>Unirrigated</th>
<th>50% criterion</th>
<th>75% criterion</th>
<th>50% - unirrigated</th>
<th>75% - unirrigated</th>
<th>75% - 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doon</td>
<td>0.01</td>
<td>0.32</td>
<td>0.71</td>
<td>0.31*</td>
<td>0.70*</td>
<td>0.39</td>
</tr>
<tr>
<td>Sutherland</td>
<td>0.19</td>
<td>0.70</td>
<td>1.08</td>
<td>0.51</td>
<td>0.89*</td>
<td>0.38</td>
</tr>
<tr>
<td>Ames</td>
<td>0.26</td>
<td>1.07</td>
<td>2.05</td>
<td>0.81*</td>
<td>1.79**</td>
<td>0.98</td>
</tr>
<tr>
<td>Burlington-Columbus Junction</td>
<td>1.01</td>
<td>1.76</td>
<td>2.19</td>
<td>0.75</td>
<td>1.18</td>
<td>1.43</td>
</tr>
<tr>
<td>Castana</td>
<td>0.02</td>
<td>0.75</td>
<td>1.31</td>
<td>0.73**</td>
<td>1.29**</td>
<td>0.56</td>
</tr>
<tr>
<td>Cedar Rapids</td>
<td>0.91</td>
<td>1.31</td>
<td>2.10</td>
<td>0.40</td>
<td>1.19</td>
<td>0.79</td>
</tr>
<tr>
<td>Elkader</td>
<td>0.51</td>
<td>0.77</td>
<td>1.24</td>
<td>0.26</td>
<td>0.73</td>
<td>0.47</td>
</tr>
<tr>
<td>Kanawha</td>
<td>0.63</td>
<td>1.05</td>
<td>1.46</td>
<td>0.42</td>
<td>0.83</td>
<td>0.41</td>
</tr>
<tr>
<td>Norwich-Shenandoah</td>
<td>0.52</td>
<td>0.79</td>
<td>1.27</td>
<td>0.27</td>
<td>0.75</td>
<td>0.48</td>
</tr>
</tbody>
</table>

* Significant at the 0.10 level.

** Significant at the 0.05 level.
zone is that the lowest layer of extraction and layers below do not get filled to field capacity. This allows the roots to move into these layers and deplete the available soil moisture to zero. Roots may continue to live in soil layers maintained at the permanent wilting percentage if water is available in some other part of the soil (Black, 1968). In reviewing the soil-moisture profile data generated by the computer, this situation only very rarely arose and usually lasted only a few days. So the problem of the occurrence of dry layers was not considered serious.

But the question of whether irrigation of the entire profile would change the results obtained by irrigation of only the active root zone needed to be answered.

To test if this method of irrigation gives different results from the original method employed, several years of data were rerun on the computer with the new irrigation method written into the program. Years were selected which, when irrigated to within one inch of 90% of field capacity in the active root zone under the 50% criterion, did not have the soil moisture in the total profile brought to within 75% of field capacity. This, it was thought, would provide great enough differences in soil moisture so that differences in the two methods of irrigation would be apparent. Runs were made with irrigation scheduled only according to the 50% criterion since previous results showed differences in
results between the two scheduling criteria to be nonsignificant. The results are given in Table 8.

From Table 8 it can be seen that when differences occurred in the 85-day weighted stress sum (only 3 years out of 10 years tested) the method of charging the entire profile actually increased the 85-day weighted stress sum from what it was when only the active root zone was charged. But the increases were small and the stress sums themselves were so small as to cause virtually no yield reduction. (Note: One unit of stress causes a yield reduction of 118.6 kg/ha (1.89 bu/acre).) These differences would probably have been changed if the 75% scheduling criterion had been used in conjunction with the two charging methods, but the differences would probably have been equally as small as those occurring with the 50% scheduling criterion.

Also, differences in the 3-month percolation totals occurred in only 3 years out of 10. In one year charging the whole profile increased percolation slightly, and in the other two years percolation was substantially reduced by charging the whole profile. These differences can be primarily attributed to differences in the timing of irrigation and how application of irrigation water coincided with precipitation.

In 5 years out of 10 the amount of irrigation water applied was changed by charging the whole profile as opposed
Table 8. Irrigation of the active root zone vs. irrigation of the total profile

<table>
<thead>
<tr>
<th>Station</th>
<th>Year</th>
<th>85-Day Weighted Stress Sum</th>
<th>3-Month Percolation Total (inches)</th>
<th>Inches of Seasonal Irrigation Water Applied</th>
<th>Period of Stress&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Old&lt;sup&gt;b&lt;/sup&gt;</td>
<td>New&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Old</td>
<td>New</td>
</tr>
<tr>
<td>Doon</td>
<td>58</td>
<td>0.27</td>
<td>0.32</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Doon</td>
<td>63</td>
<td>0.95</td>
<td>0.95</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Doon</td>
<td>68</td>
<td>0.00</td>
<td>0.31</td>
<td>0.20</td>
<td>0.28</td>
</tr>
<tr>
<td>Doon</td>
<td>71</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Sutherland</td>
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<td>0.14</td>
<td>0.44</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Sutherland</td>
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<td>0.00</td>
<td>3.27</td>
<td>0.40</td>
</tr>
<tr>
<td>Sutherland</td>
<td>72</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Castana</td>
<td>67</td>
<td>0.16</td>
<td>0.16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Castana</td>
<td>68</td>
<td>1.48</td>
<td>1.48</td>
<td>0.75</td>
<td>0.07</td>
</tr>
<tr>
<td>Ames</td>
<td>62</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<sup>a</sup>The letters B and A under 5-Day Period of Stress refer to periods Before and After the silking date, respectively.

<sup>b</sup>Old refers to data obtained from irrigation under the 50% of field capacity criterion, bringing the soil-moisture profile to within one inch of 90% of field capacity in the active root zone.

<sup>c</sup>New refers to data obtained from irrigation under the 50% of field capacity criterion, bringing the soil-moisture profile to within one inch of 90% of field capacity in the complete profile.
Table 8 (Continued)

<table>
<thead>
<tr>
<th>Station</th>
<th>Year</th>
<th>OLD 1st Sequence</th>
<th>OLD 2nd Sequence</th>
<th>OLD 3rd Sequence</th>
<th>NEW 1st Sequence</th>
<th>NEW 2nd Sequence</th>
<th>NEW 3rd Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Begin</td>
<td>End</td>
<td>Begin</td>
<td>End</td>
<td>Begin</td>
<td>End</td>
</tr>
<tr>
<td>Doon</td>
<td>58</td>
<td>7-1</td>
<td>7-7</td>
<td>7-25</td>
<td>8-12</td>
<td>9-25</td>
<td>9-28</td>
</tr>
<tr>
<td>Doon</td>
<td>63</td>
<td>7-1</td>
<td>7-25</td>
<td>8-22</td>
<td>8-31</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>68</td>
<td>7-1</td>
<td>7-4</td>
<td>7-11</td>
<td>7-20</td>
<td>8-5</td>
<td>8-29</td>
</tr>
<tr>
<td>Doon</td>
<td>71</td>
<td>7-20</td>
<td>8-16</td>
<td>9-20</td>
<td>9-23</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>58</td>
<td>7-6</td>
<td>7-18</td>
<td>8-9</td>
<td>8-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sutherland</td>
<td>68</td>
<td>7-1</td>
<td>7-16</td>
<td>7-29</td>
<td>8-25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sutherland</td>
<td>72</td>
<td>7-2</td>
<td>7-11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Castana</td>
<td>67</td>
<td>7-29</td>
<td>8-10</td>
<td>9-5</td>
<td>9-11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Castana</td>
<td>68</td>
<td>7-3</td>
<td>7-15</td>
<td>7-27</td>
<td>8-8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ames</td>
<td>62</td>
<td>8-13</td>
<td>8-22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
to just charging the active root zone. In three of those years, charging the whole profile increased the amount of irrigation water applied, and in the other 2 years charging the whole profile decreased the amount of irrigation water applied.

The major differences in the results obtained between the two irrigation methods were in the timing of irrigation. In 7 out of 10 years the timing was changed by charging the entire profile instead of just the active root zone. In four of those years, charging the entire profile caused irrigation to continue an average of 8.25 days later into the season. In the other 3 years charging the entire profile caused irrigation to stop an average of 18.33 days earlier in the season than when charging just the active root zone. The results, then, are such that no generalizations can be made about the effective change in irrigation timing due to charging the entire profile as opposed to charging the active root zone.

A very important point should be made here. Years for comparison of irrigation methods were selected under a criterion which should have provided the greatest chance to observe differences. Only 10 out of the 180 years of data used in this study met this criterion, and in these 10 years only small differences were noted between the two irrigation methods, especially with respect to the moisture stress index.
Effects of Preseason Irrigation

After looking at the output generated by the soil-moisture program and the irrigation subroutine, it was seen that in several years there occurred some moisture stress which was not removed by the regular season irrigation. Most of the moisture stress that was not removed by irrigation was one of two kinds:

1. Moisture stress which occurred prior to the starting of the regular season irrigation on July 1. This condition occurred in 29% of the years studied. The average pre-July stress was 1.50 units, causing a yield reduction of 178 kg/ha (3 bu/acre). The range of pre-July stress values was 0.05 to 11.22 units.

or

2. Moisture stress which occurred after July 1. This moisture stress occurred in very dry years when irrigation water could not be put on fast enough; i.e., in very dry years it takes quite a few days to charge a very depleted profile to a point where moisture stress due to high atmospheric demand and low soil moisture is eliminated.

Both of these two kinds of moisture stress could be removed or lessened by the watchful irrigator starting the irrigation system earlier than July 1. But a potential conflict
may then develop between early irrigation and some cultivation operations. Perhaps a better method for removing this pre-July moisture stress would be with preseason irrigation.

The method used for preseason irrigation was described previously in the Data and Procedures section. To say that this method of studying the effects of preseason irrigation is crude is probably a gross understatement. But the original purpose here was not to study in depth or accurately the effects of preseason irrigation. Rather, the primary objective of using preseason irrigation was to see if some of the stress which developed prior to July 1 and shortly after regular season irrigation began in a few very dry years could have been removed if the soil-moisture profile had been charged to some degree before planting.

By choosing years for preseason irrigation which were very dry in the spring (initial soil-moisture profile less than 40% of field capacity) it was thought that some of the more obvious and dramatic responses to preseason irrigation would be seen. This ignores situations in which preseason irrigation is dictated by dry fall conditions, and the potential excess moisture problems it would cause in conjunction with heavy fall, winter, and spring precipitation. But the soil-moisture program does not see excess moisture in the spring as a problem, and dumps all of the excess out
of the profile on May 1, so there is currently no way of evaluating this problem.

The 80% of field capacity value used as the starting soil-moisture profile under conditions of preseason irrigation is purely arbitrary. It is meant to show a condition in which the irrigator has been conservative in his application of preseason irrigation water as a hedge against the event of heavy precipitation in the fall, winter, and spring.

In Tables 9 and 10 the results of preseason irrigation plus irrigation under the 50% criterion are compared to the results of irrigation under the 50% criterion without preseason irrigation. Preseason irrigation causes a variety of effects on the 85-day weighted stress sum, seasonal percolation total, amount of seasonal irrigation water applied, the timing of irrigation, and the times at which stress occurs. With regard to the first three quantities given, only the amount of seasonal irrigation water applied at Doon is different by an amount which is statistically significant due to using preseason irrigation. Most of the other quantities are changed when using preseason irrigation, but the difference is not statistically significant.

However, certain trends are evident for the three western stations (Doon, Sutherland, and Castana) where the alternate criterion for picking years for preseason irrigation gave a larger sample size than for the other stations used.
Table 9. Changes in results due to the use of preseason irrigation

<table>
<thead>
<tr>
<th>Station</th>
<th>Year</th>
<th>85-Day Weighted Stress Sum</th>
<th>Season Percolation Total (inches)</th>
<th>Inches of Seasonal Irrigation Water Applied</th>
<th>Period of Stress&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W/O&lt;sup&gt;b&lt;/sup&gt;</td>
<td>W&lt;sup&gt;c&lt;/sup&gt;</td>
<td>W/O</td>
<td>W</td>
</tr>
<tr>
<td>Doon</td>
<td>58</td>
<td>0.27</td>
<td>0.11</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Doon</td>
<td>59&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.16</td>
<td>0.00</td>
<td>0.00</td>
<td>1.58</td>
</tr>
<tr>
<td>Doon</td>
<td>62</td>
<td>0.00</td>
<td>0.00</td>
<td>0.08</td>
<td>0.00</td>
</tr>
<tr>
<td>Doon</td>
<td>63</td>
<td>0.95</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Doon</td>
<td>64</td>
<td>0.00</td>
<td>0.29</td>
<td>2.13</td>
<td>2.93</td>
</tr>
<tr>
<td>Doon</td>
<td>65</td>
<td>0.23</td>
<td>0.54</td>
<td>2.43</td>
<td>4.28</td>
</tr>
</tbody>
</table>

<sup>a</sup>B and A are the same as in Table 8.

<sup>b</sup>W/O refers to data obtained from irrigation under the 50% of field capacity criterion without the use of preseason irrigation.

<sup>c</sup>W refers to data obtained from irrigation under the 50% of field capacity criterion with the use of preseason irrigation.

<sup>d</sup>Years picked under the criterion of initial soil-moisture profile less than or equal to 40% of field capacity. All other years picked under the criterion of initial soil-moisture profile less than or equal to 70% of field capacity.
<table>
<thead>
<tr>
<th>Station</th>
<th>Year</th>
<th>85-Day Weighted Stress Sum</th>
<th>Season Percolation Total (inches)</th>
<th>Inches of Seasonal Irrigation Water Applied W/O</th>
<th>Period of Stress W/O</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doon</td>
<td>66</td>
<td>0.00 0.00</td>
<td>0.00 0.00</td>
<td>10 9</td>
<td>6B, 5B, 4B</td>
<td>4A, 5A</td>
</tr>
<tr>
<td>Doon</td>
<td>67</td>
<td>0.00 0.00</td>
<td>0.00 2.23</td>
<td>13 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doon</td>
<td>68</td>
<td>0.00 0.00</td>
<td>4.39 5.02</td>
<td>15 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doon</td>
<td>70</td>
<td>1.49 0.07</td>
<td>2.01 1.69</td>
<td>17 12</td>
<td>6B, 5B, 4B</td>
<td>4A, 5A</td>
</tr>
<tr>
<td>Doon</td>
<td>71</td>
<td>0.00 0.00</td>
<td>0.00 0.95</td>
<td>12 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doon</td>
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<td>0.00 2.72</td>
<td>4 0</td>
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<td></td>
</tr>
<tr>
<td>Doon</td>
<td>74</td>
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<td>11 9</td>
<td>3B, 2B</td>
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<tr>
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</tr>
<tr>
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<td>8B, 7B</td>
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<td>0.00 0.00</td>
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</tr>
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<td>5B</td>
<td>1A</td>
</tr>
<tr>
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<td>10 9</td>
<td></td>
<td>1B</td>
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<td>0.00 2.68</td>
<td>9 6</td>
<td>2B, 1B</td>
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</table>
Table 9 (Continued)

<table>
<thead>
<tr>
<th>Station</th>
<th>Year</th>
<th>85-Day Weighted Stress Sum</th>
<th>Season Percolation Total (inches)</th>
<th>Inches of Seasonal Irrigation Water Applied</th>
<th>Period of Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W/O b W c</td>
<td>W/O W</td>
<td>W/O W</td>
<td></td>
</tr>
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<td>6.08 5.73</td>
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</tr>
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<td>0.63 4.02</td>
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<td>4A 5A</td>
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<tr>
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<td>0.00 0.00</td>
<td>15 14</td>
<td>6B,5B,1B, 6B,5B,1A,1A 2A</td>
</tr>
<tr>
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<td>0.00 0.55</td>
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<td>1A,2A 1A,2A</td>
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<td></td>
</tr>
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<td>Ames</td>
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<td>2A,3A 2A</td>
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<tr>
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<td>65</td>
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<td>8-18</td>
<td>8-28</td>
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<tr>
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<td>68</td>
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<td>8-6</td>
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<td>7-25</td>
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<td>7-2</td>
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</table>
For Doon, Sutherland, and Castana, preseason irrigation tended to reduce the average weighted stress sum for the 85-day period surrounding silking. Also for these three stations, preseason irrigation tended to increase the average seasonal percolation total and to reduce the amount of irrigation water applied during the regular irrigation season which begins on July 1 (Table 10).

The number of years tested at Ames, Kanawha, and Norwich-Shenandoah is really too small to even describe tendencies in quantity changes due to preseason irrigation. There are also changes in the timing of regular season irrigation (when it begins and ends, and how many sequences are used) when preseason irrigation is used. These changes can be seen in Table 9. Preseason irrigation does not consistently change the timing of regular season irrigation in one direction or another, so general comments are hard to make. But in a majority of the years considered (26 out of 48 years), preseason irrigation shifted the starting date for seasonal irrigation to a later date. The average number of days preseason irrigation moved the starting date of seasonal irrigation back was 7.20 days. The range was starting 25 days earlier to 39 days later when preseason irrigation was used.

No consistent shift in the time that stress occurred due to the use of preseason irrigation can be picked out.
Table 10. Average results for years in which preseason irrigation supplements regular season irrigation compared to the average results from the same years with only regular season irrigation employed, for three western Iowa stations

<table>
<thead>
<tr>
<th>Station</th>
<th># of Years Out of 20</th>
<th>Average 85-Day Weighted Stress Sum</th>
<th>Average Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W</td>
<td>W/O</td>
</tr>
<tr>
<td>Doon</td>
<td>14</td>
<td>0.07</td>
<td>0.23</td>
</tr>
<tr>
<td>Sutherland</td>
<td>13</td>
<td>0.14</td>
<td>0.20</td>
</tr>
<tr>
<td>Castana</td>
<td>12</td>
<td>0.34</td>
<td>0.59</td>
</tr>
</tbody>
</table>

<sup>a</sup> "-" indicates that preseason irrigation decreases the quantity.

<sup>b</sup> "+" indicates that preseason irrigation increases the quantity.

** Significant at the .05 level.
<table>
<thead>
<tr>
<th>Average Season Percolation Total (in.)</th>
<th>Average Change</th>
<th>Average Amount of Seasonal Irrigation Water Applied (in.)</th>
<th>Average Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>W/O</td>
<td>+0.86&lt;sup&gt;b&lt;/sup&gt;</td>
<td>W</td>
</tr>
<tr>
<td>1.66</td>
<td>0.80</td>
<td></td>
<td>2.24</td>
</tr>
<tr>
<td>2.99</td>
<td>1.85</td>
<td>+1.14</td>
<td>6.83</td>
</tr>
</tbody>
</table>

<sup>b</sup> Indicates significant change at the 0.05 level.
But in most cases the periods of stress were different.

One of the reasons for doing preseason irrigation was to remove stress which occurred in the spring of dry years. But as can be seen from Table 9, the criterion of picking years for preseason irrigation by choosing those years in which the starting soil-moisture profile is less than or equal to 70% of field capacity forces the use of preseason irrigation in a considerable number of years in which there was no stress when irrigated only with the regular season irrigation system (20 out of 48 years).

Also, there are five other years which have more than negligible stress (greater than one unit) which do not qualify for preseason irrigation under the criteria used. These years do not have what could be considered dry initial profiles in the spring. But very little rain occurs in these springs and the atmospheric demand is so great that the moisture in the root zone is depleted to a state in which stress occurs. The best way to remove or reduce this stress would be to start the regular season irrigation before July 1.

It is important to note that these are only 5 years out of 180 years of data considered. The 5 years are from three different stations so that it is hardly worthwhile developing a new irrigation scheme to fit these circumstances. In a real situation an operator could see this early stress
developing and could take appropriate steps for irrigation before July 1.

Note

In some recent work by Shaw (Department of Agronomy, Iowa State University, Ames, Iowa, personal communication, 1979) which looked at the data of Doon in relation to varying fertility and rotation practices, it was found that yields were better predicted by the regression equation used in this study if the program were restricted to use the 5-foot rooting profile in all years. The result of using the 7-foot rooting profile in dry spring years caused too much of a reduction in the moisture stress index, giving yields which were too high. It appears, then, that perhaps the corn crop at the Doon location does not root to 7 feet even when spring conditions are dry, or perhaps there is very little moisture available in the 5- to 7-foot layer. More rooting depth and subsoil moisture data are needed.

The implications of these results on the present study further reinforce the feeling that irrigation will be an effective practice in northwest Iowa. The effects of moisture stress at Doon are more severe than indicated previously and, hence, the improvement in yields due to irrigation would be even greater than reported in an earlier section.
SUMMARY

A study of the irrigation potential of corn on high water-holding capacity soils in Iowa was conducted by computer simulation. A computer model which used spring soil-moisture, daily rainfall, and daily pan evaporation data to estimate the moisture balance of a growing corn crop was used to determine a weighted seasonal stress index. This weighted seasonal stress index was used in a regression equation to estimate corn yields.

The effects of irrigation were simulated by incorporating into the soil-moisture program a subroutine which added one inch of effective irrigation water to the soil profile every 3 days. This was meant to simulate the effects of a large, center-pivot, sprinkler irrigation system.

Nine stations were chosen to determine the differential effects of irrigation across the state of Iowa. All nine of the Iowa crop reporting districts were represented except the south-central district. It was felt that the results from the south-central district would not be much different from the results from southeastern Iowa.

Soil-moisture, rainfall, and pan evaporation data for the period of 1958-1977 were used in the computer simulation. Although data were available for a longer period of record, a 20-year period was selected to avoid biasing the
results due to the approximately 22-year drought cycle.

Two methods for scheduling irrigation were tested:

1. Irrigation initiated when the soil moisture in the active root zone was reduced to 75% of the amount of water available at field capacity for the active root zone.

2. Irrigation initiated when the soil moisture in the active root zone was reduced to 50% of the amount of water available at field capacity for the active root zone.

The effects of irrigation on percolation (excess moisture problems) was looked at by comparing July, August, and September percolation sums. The results obtained by irrigation of the active root zone were compared to results obtained by irrigation of the entire profile for selected years to determine if there were major differences in the two irrigation methods. The effects of charging the profile with a preseason irrigation prior to planting were investigated for a few selected years.

The following is a summary of the results obtained in this study:

1. Corn yields are reduced by moisture stress to some degree almost every year at most Iowa locations. These reductions in yield are greatest in northwest Iowa and least in east and southeast Iowa.
2. When irrigation is used, yield reductions due to moisture stress are minimal, if they exist at all. Irrigated yields across the state fall in the range of 9250-9750 kg/ha (147-155 bu/acre).

3. Increases in corn yields due to irrigation were greatest in northwest Iowa (average yield increase of 2197 kg/ha (35 bu/acre)), and least in east and southeast Iowa (average yield increase of 628 kg/ha (10 bu/acre)).

4. Seasonal irrigation application amounts are greatest in northwest Iowa and least in east and southeast Iowa. The range of irrigation amounts is quite large, especially in the western and central thirds of the state, clearly showing the results of variable moisture conditions that occur from year to year across the state.

5. The frequency of a wetness problem (measured as increased percolation) is higher in the eastern and southeastern parts of Iowa, and lower in the northwestern part of the state. The frequency of a wetness problem is increased when irrigation is used.

6. There is no significant difference in the yields obtained when using the 75% of field capacity scheduling criterion as opposed to the 50% of field capacity scheduling criterion.

7. Irrigation scheduled according to the 75% criterion increases the amount of seasonal irrigation water applied as
compared with scheduling according to the 50% criterion for all nine stations tested, but only at Cedar Rapids is the difference statistically significant.

8. The frequency of a wetness problem (measured as increased percolation) is higher for all nine stations tested when irrigation is scheduled under the 75% criterion as compared with irrigation scheduled under the 50% criterion. The differences between percolation amounts under the 50% criterion and the 75% criterion are not significant at any station.

9. The method of irrigating by charging the entire soil profile as compared with charging just the active root zone does not produce any consistent changes in moisture-stress amounts, irrigated yields, irrigation application amounts, or percolation frequencies and amounts. These quantities are changed to some degree, but only as they are affected by changes in the timing of irrigation, and these changes in the timing of irrigation are not predictable. The number of years out of the total studied in which changes in the above quantities would be significantly changed due to changing the method of irrigation is very small.

10. Preseason irrigation causes a variety of effects on the 85-day weighted stress sum, amount of seasonal irrigation water applied, seasonal percolation total, the timing of irrigation, and the times at which stress occurred. Most
of these quantities are not different by a statistically significant amount due to using preseason irrigation. But at Doon, Sutherland, and Castana, preseason irrigation tends to decrease the average 85-day weighted stress sum, increase the average seasonal percolation total, and decrease the amount of irrigation water applied during the season. Also, preseason irrigation tends to shift the beginning date for regular season irrigation to a later date. Preseason irrigation is not always effective in reducing pre-July moisture stress, especially in years with very dry spring conditions accompanied by high atmospheric demand.
CONCLUSIONS

From this study it appears that irrigation can be used to reduce moisture stress and raise corn yields to some degree almost every year at most Iowa locations on high water-holding capacity soils. Stations such as Doon, Sutherland, and Castana, located in northwest and west Iowa, have the greatest potential for frequent use of substantial amounts of irrigation water to increase corn yields. Other areas of the state could benefit from irrigation in a large percentage of years, but this benefit is not as great and does not occur as often as in western Iowa.

There seems to be no yield advantage to scheduling irrigation according to the stricter criterion (75% of field capacity). Since less irrigation water is applied, and the risk of a wetness problem is reduced by scheduling irrigation according to the 50% of field capacity criterion, this method is the better of the two scheduling criteria tested. Although it is possible that the 75% scheduling criterion would provide more protection against stress that would occur if a heat wave and the resultant high atmospheric demand occurred just as the 50% scheduling criterion is reached, it is felt from the results of this study that this situation would not occur very often, and only small amounts of stress would accumulate before the profile is
adequately recharged by irrigation with the 50% scheduling criterion.

It is difficult to say from the results of this study whether preseason irrigation is a worthwhile operation in Iowa. Perhaps a better investment of time and energy would be in watching weather, crop, and soil-moisture conditions carefully so that irrigation could be initiated sooner than July 1 if the need arose.

From a purely climatological standpoint it can be concluded that irrigation provides an effective means for increasing yields by reducing moisture stress for most of the state of Iowa, but the greatest and most frequent responses to irrigation are seen in western and northwestern Iowa.
BIBLIOGRAPHY


ACKNOWLEDGMENTS

The author wishes to express his appreciation to all of the members of the Agricultural Climatology group at Iowa State University for their help and encouragement throughout the course of the author's graduate study and thesis preparation. A special thanks goes to Dr. Robert H. Shaw for his guidance in setting up the author's graduate program and in reviewing the thesis project throughout its course of progress.

The author also wishes to sincerely thank Dr. Douglas N. Yarger for having directed him toward the study of agricultural climatology at Iowa State University. The appreciation the author feels for Dr. Yarger due to his guidance cannot be expressed in words.
SUBROUTINE IRR(SMP,FC,IPAV,IPAV1,ICDAY,KRT1,BOT,TOTIRR,P,APLIR,
1OUTBOT,ISTART)
DIMENSION SMP(10),FC(10),BOT(10),P(5)
C THIS SUBROUTINE SIMULATES IRRIGATION OF A POINT IN A LARGE FIELD.
C THE FIELD IS IRRIGATED WITH A CENTER PIVOT SPRINKLER IRRIGATION SYSTEM
C SET TO APPLY 1" OF WATER TO A GIVEN POINT EVERY THREE DAYS, IF
C REQUIRED; I.E., IT TAKES THREE DAYS FOR THE SYSTEM TO MAKE A COMPLETE
C CYCLE.
C IF LESS THAN 1" IS REQUIRED THEN DO NOT IRRIGATE AND SHUT SYSTEM OFF.
C ICDAY=DAY OF THE IRRIGATION CYCLE (1,2 OR 3)
C APPLY=AMOUNT OF WATER IRRIGATION SYSTEM APPLIES ON A GIVEN DAY TO THE
C POINT OF GROUND WE ARE CONSIDERING (1" OR 0")
C RZFC=ROOT ZONE FIELD CAPACITY
C RZSMP=ROOT ZONE SOIL MOISTURE PROFILE
C AMTIRR=AMOUNT OF IRRIGATION WATER THAT NEEDS TO BE APPLIED TO BRING
C SOIL MOISTURE UP TO 90% OF FIELD CAPACITY (IN ACTIVE ROOT ZONE)
C ISTART=SIGNAL TO SHOW IF IRRIGATION SYSTEM IS ON (ISTART=1) OR
C OFF (ISTART=0)
C TOTIRR=THE TOTAL AMOUNT OF IRRIGATION WATER APPLIED FOR THE SEASON
C APLIR=THE AMOUNT OF APPLIED IRRIGATION WATER FOR A GIVEN DAY
C P(1)=THE FIRST DAY FOR THE ANTECEDENT PRECIPITATION INDEX CALCULATION
C DIFIR=THE AMOUNT OF WATER NEEDED TO BRING A GIVEN LAYER TO FIELD
C CAPACITY
C OUTBOT=AMOUNT OF MOISTURE WHICH PERCOLATES OUT OF THE BOTTOM OF THE
C 10-LAYER PROFILE DUE DIRECTLY TO OVERIRRIGATING. THE VALUE OF OUTBOT
C SHOULD ALWAYS BE 0 IF THE PROGRAM IS WORKING CORRECTLY
C RTOP=TOTAL AMOUNT OF MOISTURE IN THE ACTIVE ROOT ZONE
IF(ICDAY.LT.3) GO TO 1004
GO TO 1005
1004 ICDAY=ICDAY+1
APPLY=0.0
RETURN
1005 RZFC=0.0
RZSMP=0.0
DO 1006 II=1,KRT1
RZFC=RZFC+FC(II)
RZSM= RZSM+ SMP(I1)

1006 CONTINUE

RZSM = RZSM+ SMP(I1)

1041 APPLY = 1.0

TOTAL = TOTAL + APPLY

APLIR = APPLY

P(1) = P(1) + APPLY

DIFIR = FC(I2) - SMP(I2)

IF (APPLY .GE. DIFIR) GO TO 1012

SMP(I2) = SMP(I2) + APPLY

GO TO 1013

1012 APPLY = APPLY - DIFIR

OUTBOT = OUTBOT + APPLY

1013 ICDAY = 1

ISTART = 1

RTOP = 0.0

DO 1014 13 = 1, KRT1

RTOP = RTOP + SMP(I3)

1014 CONTINUE

IPAV = (RTOP / BOT(KRT1)) * 100.0 + 0.5

IPAV1 = ((SMP(1) + SMP(2)) / BOT(2)) * 100.0 + 0.5

RETURN

END