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thesis entitled

AN ANALYSIS OF IRRIGATION UNIFORMITY

AND SCHEDULING EFFECTS ON SIMULATED MAIZE YIELD

IN HUMID REGIONS

presented by

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has been accepted towards fulfillment
of the requirements for

Master of Science degree in Ag. Eng. Technology

Major professor

Date Aug. 6, 1987

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AND SCHEDULING EFFECTS ON SIMULATED MAIZE YIELD
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A THESIS

Submitted to
MICHIGAN STATE UNIVERSITY
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

in

Agricultural Engineering Technology

Department of Agricultural Engineering

1987

ABSTRACT

AN ANALYSIS OF IRRIGATION UNIFORMITY
AND SCHEDULING EFFECTS ON SIMULATED MAIZE YIELD
IN HUMID REGIONS

By

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The objective of irrigation in humid regions is to supply sufficient water to meet crop requirements during short-term droughts. In addition to supplying an adequate volume of water, an irrigation system should distribute this water uniformly. Uniformity is an index inversely related to the variance of irrigation depth. In some cases where uniformity is sub-optimal, adverse yield effects may be lessened through more frequent water application. Most research into the relationship between uniformity, scheduling and yield has been of a theoretical nature, thus the first objective of this research was to determine, using a crop model and irrigation scheduling program, the effects of irrigation uniformity and scheduling on maize yield.

Irrigation uniformity is commonly measured using evenly spaced collectors over which the irrigation system is operated. This method of assessment only considers an

initial level of uniformity as applied by the irrigation technology. Several factors, such as uniform rainfall during the growing season, may serve to mitigate the effects of non-uniform irrigation. The second objective of this research was to assess the effects of rainfall on overall water application uniformity and efficiency. The third objective of this research was to analyze and discuss these new insights into irrigation uniformity with respect to economics and farm management.

The results of this research have shown that there is a relationship between irrigation uniformity , yield uniformity and mean yield. In addition, rainfall is an important factor in improving overall uniformity in humid regions. The use of a coefficient of variation adjusted for rainfall leads to more accurate assessments of yield losses due to non-uniformity.

Economic analysis showed that irrigation scheduling at a higher available water content is not beneficial in humid regions; however is appropriate in arid areas if water and energy costs are low. Substantial rainfall inputs also influence farm management, especially in decisions concerning irrigation technology selection and improvement.

To Geech,

who lay at my feet through the worst of it all.

ACKNOWLEDGEMENTS

The author wishes to sincerely thank Dr. John Gerrish, Mr. Alan Herceg, Dr. Joe Ritchie and especially Dr. Vincent Bralts for their contributions to, and support of this research.

Special thanks go to Ken Algozin and Ed Martin for their invaluable assistance in data presentation and analysis.

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I. INTRODUCTION

Irrigation in the engineering sense, is the application of water by artificial means (i.e. via some technology) for agricultural or horticultural crop growth. In very arid regions, irrigation is often the only way to meet crop water requirements and insure yield. Hence irrigation has been practiced in many of these areas for centuries. In humid locations, supplemental irrigation is a fairly recent though rapidly expanding phenomenon. In Michigan, 3% of the total cropland was irrigated as of 1978 (ERS, 1984). In 1980, a Cooperative Extension survey reported that Michigan's irrigated land area comprised over 400,000 acres, a 200% increase since 1975. Although the rapid expansion of irrigated cropland has slowed somewhat in recent years, irrigation will continue to be an important technology on many Michigan farms.

The objective of irrigation in humid regions such as Michigan, is to provide sufficient water to meet crop demands during short term drought periods. The extent to which this objective is met by an irrigation system is dependent upon both design and management factors. Design factors include the proper selection of irrigation system and pumping station components to insure adequate capacity for water delivery to the crop. Management factors include the accurate assessment of crop water requirements and subsequent scheduling of irrigations to meet these requirements. Irrigation scheduling may be accomplished with varying degrees of success by many different means including : (a) direct or indirect assessment of soil water status, (b) evaluation of plant stress, and (c) estimate of evapotranspiration and soil water status through the use of climate and water balance numerical models. One of the most widely accepted and successful methods of irrigation scheduling is through the use of numerical models which estimate ET and calculate soil water status. With the advent of microcomputers and the development of irrigation scheduling software such as SCHEDULER (Driscoll and Bralts, 1986), extension services, agricultural consultants and irrigators themselves, are now able to solve the necessary equations with a microcomputer and schedule irrigation in a matter of minutes.

Irrigation uniformity is a measure of the variability of the application of water to an irrigated area. The degree of irrigation uniformity also depends on technology design and management and is related to crop yield through the effects of over and under watering. In non-uniform irrigation situations, deficit areas exhibit yield loss due to plant stress. Areas where excess water has been applied may also show decreased yield because of nutrient leaching and reduced root aeration.

Even with a good design, all irrigation systems exhibit some degree of non-uniformity. If an irrigation system is to be properly managed to minimize the costs of yield and nutrient loss associated with the system's non-uniformity, an appropriate irrigation schedule must be found. In the case of a poor design or a loss irrigation system uniformity over time, management through scheduling may also be important. There is some level however, where the cost of non-uniformity exceeds the cost of improving the irrigation technology, regardless of the irrigation schedule.

The availability of sophisticated crop models such as the CERES-Maize corn model (Jones and Kiniry, 1986) allow for accurate estimates of the yield effects of excess and deficit water on a crop. As Dent and Blackie (1979) have noted, there are distinct advantages to using simulation models over field based experimentation. These advantages include: (1) total control over the experimental environment and treatment; (2) time constraints are reduced to that required for computer operations; and (3) treatments are evaluated sequentially as opposed to simultaneously in actual field experiments. One of the objectives of this research then, will be to use the standard version of the CERES-Maize model to analyze the effects of different center-pivot irrigation uniformity levels and scheduling strategies on maize yield.

Uniformity of center pivot irrigation is commonly measured using collectors of equal size placed at constant intervals along the radius of the pivot. The pivot is turned on and allowed to pass over the collectors. The volume of water in each can is then measured and uniformity is calculated. This method of measurement only considers an initial uniformity of water as it is applied by the irrigation system. Several other factors, however may influence the final level of water uniformity in the field. On an instantaneous basis (i.e. after one irrigation event) lateral movement of water in the soil may significantly increase the final uniformity of soil water. Over an entire season, uniform application of water through periodic rainfall will affect the overall seasonal uniformity of water applied to an irrigated area. A second major objective of this research will be to determine the effect of rainfall on uniformity of water application.

The third objective of this research will be to analyze and discuss these new insights into irrigation uniformity with respect to economics and farm management decision making.

A. Background

There are numerous methods available for irrigation water application. These methods may be divided into four general categories: (a) subsurface (b) surface (c) drip/ trickle, and (d) above ground sprinkler.

Above ground sprinkler is by far the most prevalent irrigation method in humid regions including Michigan. The most commonly used sprinkler irrigation technologies are center pivot and big gun. Solid set and hand move sprinklers are also used to irrigate high value horticultural crops. System expense, however prohibits their use in field crops. Sprinkler irrigation, particularly center pivot and big gun systems are popular primarily because of their relatively low per acre cost and their versatility. Sprinkler irrigation is appropriate for a wide range of topographies, soils and crops. Because of the importance of center pivot sprinkler irrigation in Michigan and other humid areas, this work will focus on uniformity under center pivot sprinkler systems. Figure 1 on the following page is a schematic diagram of center pivot operation.

The previously noted irrigation system categories may also be differentiated by cost and by application efficiency characteristics. Generally, drip irrigation is more efficient (and expensive) than sprinkler irrigation which in turn, is more efficient (and expensive) than surface irrigation.

It should be noted that many different efficiency concepts exist and are widely used. Care must be taken to determine the precise definition of a particular concept and all terms which are included in it. In this study, irrigation efficiency refers to a ratio of

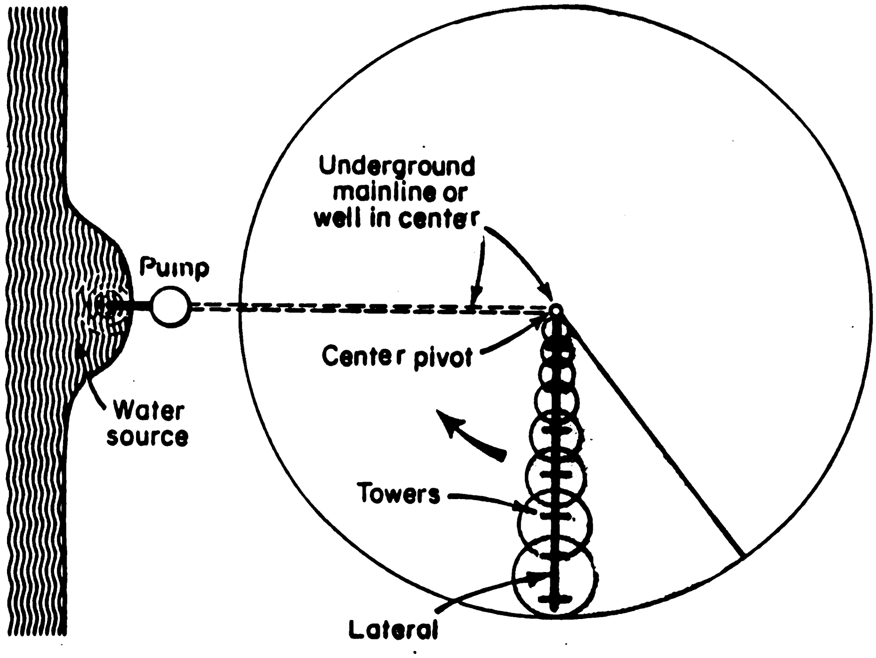

Figure 1. Center Pivot system design (Kay, 1983).

beneficially used water to total water applied. "Beneficial use" is a cloudy and often subjective term which may lead to over or under estimation of the efficiency of a given system or systems. Application efficiency, in contrast to irrigation efficiency, is the ratio of water stored in the root zone to total water applied. These two definitions are most likely to differ when leaching water is required. Although this water is not stored in the rootzone, it is generally considered beneficially used. Consequently, when leaching water is required in a system, the calculated irrigation efficiency will be higher than the application efficiency. In Michigan, where high precipitation alleviates the need for leaching water, irrigation efficiency is synonymous with application efficiency.

B. Justification

In 1983, Michigan State University in cooperation with the St. Joseph County Cooperative Extension Service and Soil Conservation Service developed a program for local irrigators which included an irrigation system evaluation service. See Appendix A for an overview of the evaluation method used for center pivot irrigation. During the past three years, SCS has evaluated over seventy center pivot systems and has found coefficient of variation uniformities ranging from .11 to .50 . The acceptable uniformity standard for sprinkler irrigation is found to have sub-standard uniformities.

The application of water by any irrigation system is inherently non-uniform to some degree. In addition, the level of uniformity which can be achieved by any irrigation system at the onset or when the system is improved is generally dictated by the level of capital investment. Assuming that a farmer's objective is to maximize profit, the optimization of irrigation technology is probably not economical unless water costs and/or energy costs are very high. In addition, factors such as frequent rainfall may serve to mitigate the effects of non-uniform irrigation. Thus, in some situations, low uniformities may be quite acceptable. The body of work that deals with the issue of non-uniformity and yield is primarily of a theoretical nature. The empirical relationship between irrigation uniformity and yield uniformity to be better understood. The development of sophisticated crop models such as CERES-Maize can allow for the evaluation of these theoretical principles in on-farm irrigation situations.

C. Objectives

The overall goal of this research is to determine the effects of irrigation uniformity and mitigating factors such as rainfall on the economics of irrigation in humid regions like Michigan.

The specific objectives of this research are:

1. To evaluate the mean and variance of maize yield with respect to high, medium, and low center pivot irrigation system uniformities.

2. To determine the effect of rainfall on the uniformity of irrigation systems and on the uniformity of crop yield.

3. To analyze and discuss these new insights into irrigation uniformity with respect to economics and farm management decision making.

II. LITERATURE REVIEW

To adequately address the issue of irrigation uniformity as it relates to scheduling, yield and rainfall some knowledge of (a) irrigation uniformity concepts, (b) application efficiency concepts and theory, (c) uniformity and yield relationships and (d) computer modeling of crop growth and water use is required. This section provides a review of the more pertinent literature and theory associated with these topics.

A. Irrigation Uniformity Concepts

1. Distribution Models

In sprinkler irrigation, a wide range of statistical models have been used to describe uniformity. The normal distribution has been considered by Elliott et. al.(1979,1980), English and Nuss (1982), Hart et.al. (1980) Hart and Reynolds (1965) Hill and Keller (1980) Karmeli (1978) Peri et.al. (1979) Seniwongse et.al. (1972) Su (1979), and Walker (1979) Elliott et al. (1979,1980,) have reported on the use of the beta distribution. Gamma distributions in sprinkler irrigation have been researched by Chaudry (1976,1978), Seniwongse et.al. (1972) and Su (1979).

a. Linear Model

The use of the linear or cumulative linear (uniform) models for sprinkler irrigation has been found primarily in the works of Karmeli (1977 and 1978) and Elliott et. al. (1978 and 1980). Karmeli tested 36 sets of sprinkler data with a linear model with coefficients of variation ranging from .38 to .62. He concluded that the linear model supplied a good estimate (compared with normal estimates) for higher uniformities and a superior estimate for low uniformities (UCC < 55%).

Elliott et.al. (1979 and 1980) also used linear regression to estimate the cumulative distribution function for sprinkler irrigation. In contrast to Karmeli's work, they found that the linear model was only superior to the normal for low uniformities.

The linear regression function (Y = a + bx) when used with low uniformity sprinklers can supply information as to the areas of deficit, surplus and adequate irrigation as well as area depth in deficit and surplus areas.

b. Beta Distribution

Elliott et.al. (1980) used the beta statistical distribution to describe sprinkler irrigation distribution patterns. Fitting the linear, normal and beta distributions to 2,450 overlapped sprinkler patterns with widely varying uniformities, they concluded that the beta distribution was the superior model at all uniformities, especially low ones. Although the beta distribution is quite flexible a major drawback to its use is its complexity.

c. Gamma Distribution

Chaudry (1978 and 1980) , Seniwongse et.al. (1972) and Su (1979) have all explored the gamma distribution as a method of characterization of irrigation patterns. Chaudry's work is theoretical and does not consider how well the gamma distribution represents real data. However his work is justified in that asymmetry or skewness characteristics are common in sprinkler irrigation distribution patterns. The gamma distribution can be used to account for this skewness. In addition, the normal distribution does allow for negative irrigation depths and the gamma distribution has the advantage of eliminating these.

Seniwongse et.al. (1972) found that the gamma distribution was representative of most high uniformity data, but was only moderate for medium and unacceptable for low uniformities. Su (1979) using uniformity ranges from 60 to 90% found that the gamma distribution fit his data no better than the normal distribution.

d. Normal Distribution

The normal distribution is most often used to describe sprinkler irrigation uniformities and has been found by most authors to be an acceptable representation of irrigation distribution. A major advantage of the normal distribution model is its simplicity. Only two moments, mean and standard deviation, are required to describe the distribution. Too, the normal distribution is reported to provide an adequate representation over a wide range of uniformities, sprinkler sizes and spacings (Hart and Reynolds 1965, Seniwongse et.al. 1972, Karmeli 1978).

e. Other Distribution Models

Childs and Hanks (1975) used the parabolic model to describe sprinkler pattern distributions. Although this model has some advantages in that it does not predict negative or infinite irrigation depths, it has only been used with high uniformity sprinkler patterns.

Seniwongse, Wu and Reynolds attempted representing sprinkler patterns with the poisson and exponential models but generally found that acceptable fits were not possible. Karmeli (1977) tried modeling the cumulative distribution function for sprinkler data with a variety of exponential models and found that the approach was far more complex and the results were no better than with the linear model .

2. Uniformity Measures

Uniformity measures are calculations based on estimates of irrigation depths at various locations in an irrigated area. Based on these depths, a single number is produced which may be used as an indicator of uniformity. Uniformity measures are only a function of the variation in irrigation depth, although weighting factors may be used to express a greater degree of significance of some (usually lesser) depths.

a. Christiansen's Coefficient (UCC)

The first and to this day most widely used expression of sprinkler uniformity was reported by J.E. Christiansen in 1942. This coefficient, commonly referred to as Christiansen's Coefficient symbolized by UCC or CU is expressed as a percentage and defined by the following equation:

$$UCC = 100 \left(1.0 - \frac{x}{mn} \right)$$

in which x is the sum of the absolute deviations of individual observations from the mean value m (i.e. x = $[x_i - m]$) and n is the number of observations. If the irrigation system is completely uniform, then all $x_i = m$ and UCC = 100%. Heerman and Hein have modified the above equation for use with center pivot systems such that each observation represents a different area of the field.

The resulting number contains the weighted value of the observations:

$$UCC = 100 \left(1.0 - \frac{S_s \quad D_s - \left(\dfrac{D_s \; S_s}{S_s} \right)}{D_s \; S_s} \right)$$

where D_s is the depth applied at a catch can and S_s is the distance to equally spaced collectors.

Despite its popularity, presumably due to its simplicity, Christiansen's Coefficient has been criticized extensively over its 40 year existence. Benami and Hore (1964) questioned Christiansen's assumption that the average deviation is a satisfactory measure of performance. They present an hypothetical example wherein two systems are measured and twelve readings are taken of each. In the first case, all readings deviate by +/- 20 and in the second case, eight readings deviate by +15, two readings by -15, and two reading deviate by -45 percent from the mean. In each case, the average deviation equals 20 and both systems have the same uniformity coefficient (80%). Clearly however, the first system is more uniformly distributed than the second. Benami and Hore's argument would be far more compelling if the coefficient that they present as an alternative were not subject to the same problem of arbitrariness as the UCC (Solomon, 1983).

Norum (1961 cited in Solomon 1983 and 1966) also criticized the UCC as lacking "pertinent physical significance" and as "incomplete" and "arbitrary". By this, Norum means the lack of a connection between capital cost of a system and irrigation efficiency as characterized by the UCC. At the time that Norum made these comments and continuing today, most systems are selected so that they can provide an adequate mean application with a Christiansen's Uniformity Coefficient deemed "acceptable" (generally 80% or greater). Even if a system exhibits a uniformity which is less than optimal, investment in and utilization of such a system may still be economically justifiable if water and energy costs are sufficiently inexpensive.

b. Wilcox and Swailes Coefficient (UCW)

In 1947, another uniformity coefficient was introduced by J.C. Wilcox and G.E. Swailes. Wilcox and Swailes evaluated the efficiency of several sprinkler models at different spacings. The sprinkler types are real, however the spacing assessments are purely theoretical. The authors evaluated the catch from a single sprinkler in evenly spaced cans. Then assuming that the pattern and catch would be the same for another sprinkler of the same type, the uniformity is calculated. The Wilcox and Swailes coefficient (UCW) is defined as:

$$UCW = 100\left(1 - \frac{S}{\overline{X}}\right)$$

Where S is the standard deviation of the catch can values and $\overline{X}$ is the mean. The Wilcox and Swailes coefficient of uniformity is also called the coefficient of variability or variation and the statistical uniformity.

Wilcox and Swailes as well as others have noted that because the squares of the deviations from the mean are used rather than the deviations themselves, larger deviations are given more weight. Thus, UCW is generally lower than UCC for the same system. Dabbous (1962 as reported in Solomon 1983) and Tezer (1971) both found a strong linear relationship between UCC and UCW which is generally expressed as follows:

$$UCC = 100(1 - .798\ S/\overline{X})$$

The Wilcox and Swailes coefficient or coefficient of variation has become widely used in the assessment of drip irrigation uniformity (Wu and Gitlin, 1981, Bralts and Kesner, 1983). As Wu and Gitlin note (1981) the coefficient of variation can be used to determine the average depth of deficit in the deficit area of the field. This in turn may be used to schedule irrigation in such a way that yield losses may be minimized in drip irrigated fields.

c. Hart and Reynolds Coefficient (UCH)

In 1965, Hart and Reynolds proposed another uniformity coefficient which essentially utilizes the same statistical parameters as the UCC and UCW. Assuming that non-uniform sprinkler distributions are normally distributed and since the mean deviation of normally distributed values is equal to $(\sqrt{2/\pi})$ times the standard deviation of those values they proposed:

$$UCH = 1 - [\sqrt{(2/\pi)}]\,(S/\overline{X})$$

The UCH incorporates the standard deviation to mean ratio and produces the same value as Christiansen's when irrigation depths are normally distributed.

d. Benami and Hore's Coefficient

In 1964, Benami and Hore presented what they considered to be a favorable alternative to Christiansen's coefficient. As mentioned above, the authors criticized the UCC for its arbitrary performance measurement. In addition they state that although the UCW is a somewhat better representation, it too is insufficiently sensitive to differentiate between satisfactory and unsatisfactory sprinkler performance. The Benami and Hore coefficient (UCA) is a radical departure from the previously discussed methods in that the approach is not simply a statistical evaluation of a technology irrespective of crop needs. As Solomon (1983) notes,

> " The significance of UCA is in the fact that the authors constructed it with a particular interpretation in mind. It was not merely a measure which varied with the degree of uniformity. It was intended to vary with the physical significance of uniformity... UCA incorporates not only a measure of uniformity, but a value system appropriate to the context within which uniformity measurements are used."

The UCA is based on a consideration of the deviations from the mean of a group of readings below the mean and a group above the mean:

$$UCA = C_1/C_2$$

where

$$C_1 = M_b - \frac{[x]_b}{N_b}$$

and

$$C_2 = M_a + \frac{[x]_a}{N_a}$$

M_a is the mean of a group of readings above the general mean, M_b is the mean of a group of readings below the general mean, N_a and N_b are the number of readings above and below the mean respectively. $[x]_a$ is the absolute deviation from M_a for the group of readings above the mean and $[x]_b$ is the sum of the absolute deviations from M_b for the group of readings below the mean.

The ratio of means and deviations devised by Benami and Hore tend to stress the deviations below the general mean on the assumption that yield losses due to drought stress are more significant with respect to yield and economics than are losses due to inundation.

e. SCS Pattern Efficiency (PE)

The On-Farm Irrigation Committee of the ASCE defines pattern efficiency proposed by the SCS as the ratio of the average low quarter depth of irrigation water infiltrated and stored in the rootzone to the average depth of irrigation water applied.

Because of this reference to the low quarter applied, pattern efficiency is also called the application efficiency of the low quarter or AELQ.

B. Application Efficiency Concepts and Theory

As noted previously irrigation efficiency generally refers to the ratio of water which is beneficially used to total water applied. Irrigation efficiency (sometimes called water use efficiency) is defined by the equation (Israelsen and Hansen, 1962)

$$E_u = 100 \frac{W_u}{W_d}$$

Where E_u is the water use efficiency, W_u is the water which is beneficially used and W_d is water which is delivered to the farm or irrigation system.

Another widely used efficiency concept is water application efficiency, the ratio of water stored in the rootzone to total water applied. Water application efficiency is defined by the equation

$$E_a = 100 \frac{W_s}{W_f}$$

Where E_a is the water application efficiency, W_s is water stored in the root zone during irrigation and W_f is the water delivered to the farm or irrigation system. The most common sources of loss of irrigation water during water application include surface runoff (R_f) and deep percolation below the root zone (D_f) (Israelsen and Hansen, 1962). Therefore,

$$W_f = W_s + R_f + D_f$$

and E_a may then be defined as

$$E_a = 100 \frac{W_f - (R_f + D_f)}{W_f}$$

The definitions of application efficiency and water use efficiency are most likely to differ when leaching water is required. Although this water is not stored in the rootzone, it is generally considered beneficially used. Consequently, when leaching water is required in a system, the calculated irrigation efficiency will be higher than the application efficiency.

Irrigation and/or application efficiency give no indication of irrigation uniformity or adequacy. Figure 2 shows a common application efficiency found under sprinkler irrigation. In Figure 2, area A is adequately irrigated, area B is in deficit and area C has been excessively irrigated. Using these areas, application efficiency may be calculated as A / A + C. Figure 3 shows how, with deficit irrigation, application efficiencies of 100% may be achieved (Wu and Gitlin, 1981).

For drip irrigation, Wu and Gitlin (1983) and Bralts (1984) have defined the application efficiency as

$$E_a = 100 \left(\frac{V_r(1-P_D)}{V_a} \right) = 100 \left(\frac{V_r(1-P_D)}{3600 Q_a T} \right)$$

Where V_r is the amount of water applied, P_D is the irrigation deficit expressed as a decimal, V_a is the irrigation volume required, Q_a is the actual discharge to the submain per second and T is the irrigation time in hours. The above relationship is illustrated in Figure 4 (Wu and Gitlin, 1981). In the special case where the irrigation volume applied is equal to the irrigation volume required, the irrigation deficit is equal to 0.4 times the coefficient of variation. (Bralts,1984) In this case, application efficiency can be determined by the equation

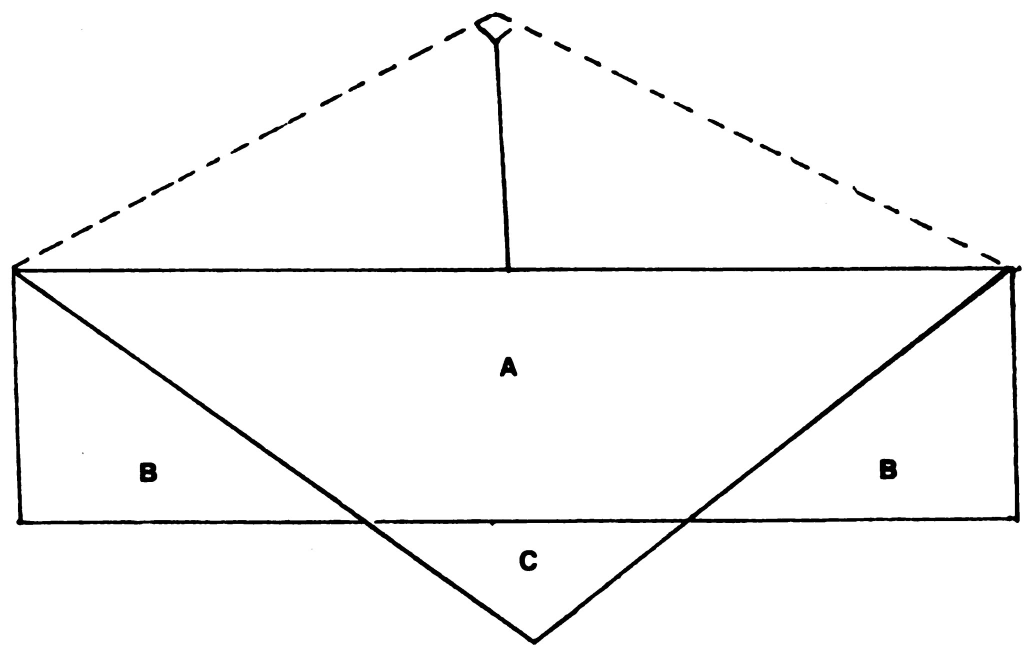

Figure 2. Application Efficiency Under Sprinkler Irrigation

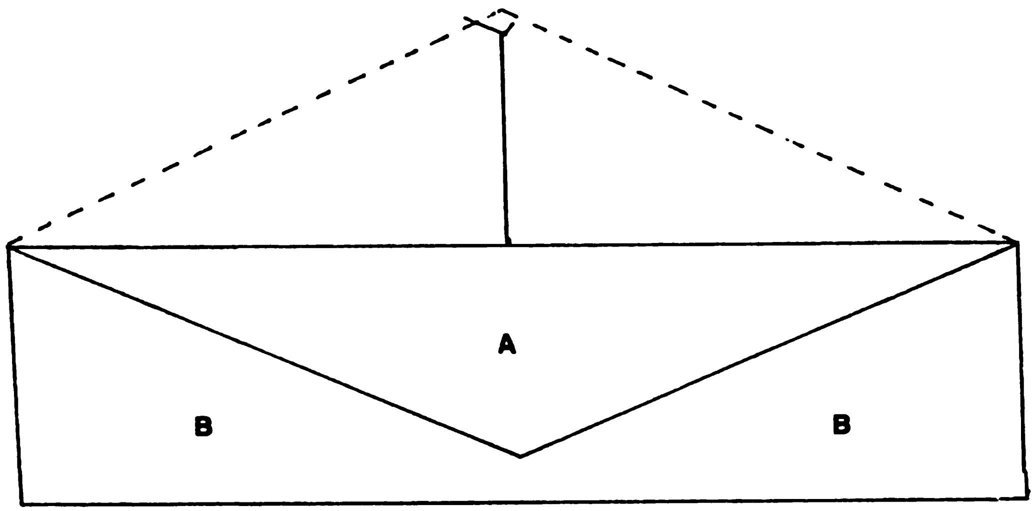

Figure 3. Deficit Irrigation for 100% Efficiency

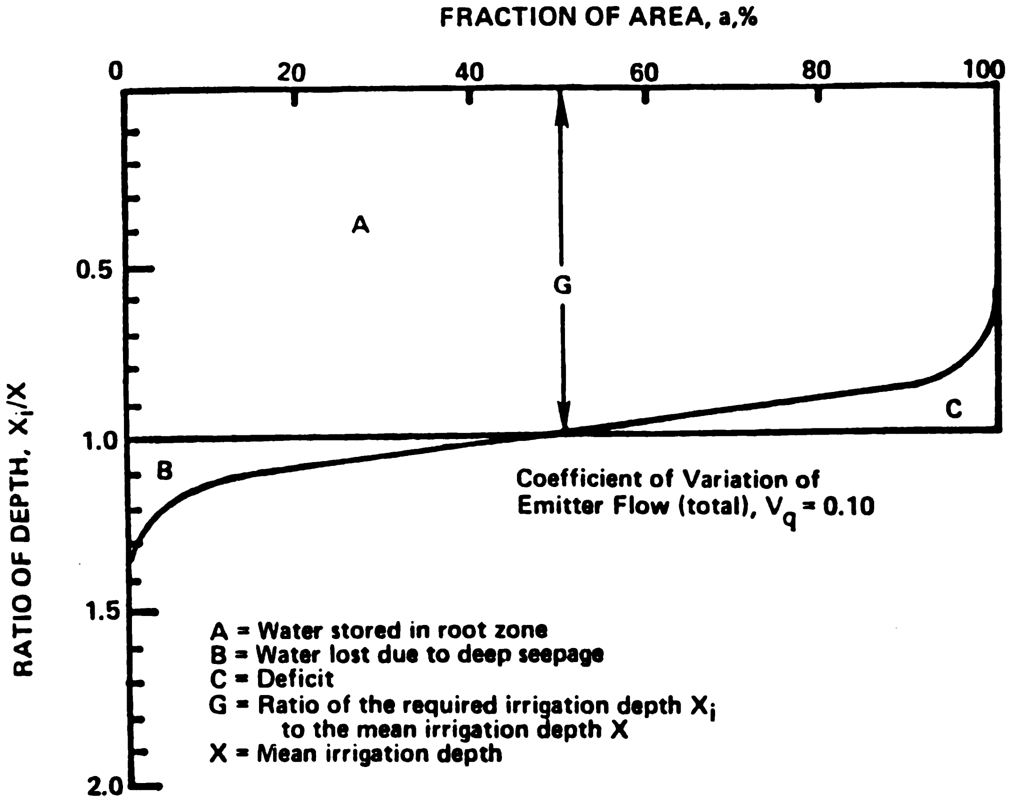

Figure 4. Application Efficiency Relationships (Bralts, 1984)

$$E_a = 100 \left(\frac{V_r(1-P_D)}{V_a} \right) = 100\ (1 - 0.4\ CV)$$

if $V_a = V_r$

This relationship between application efficiency, percent deficit, and coefficient of variation is based on probability and normal statistical distribution and is demonstrated in Figure 5 (Wu and Gitlin, 1983).

Hart and Reynolds (1964) used the coefficient of variation for analytical irrigation system design purposes. Assuming that the standard deviation and mean calculated from a population sample adequately reflect the actual mean and variance of the total population then the equation for the normal probability density function may be written as

$$y = \frac{Nq}{s\sqrt{2\pi}} e^{-\frac{1}{2}\left\{\frac{x - \bar{x}}{s}\right\}^2}$$

where N is the number of observations, q is the class interval, x is the value of an occurance , $\bar{x}$ is the mean of the sample and s is its standard deviation. If the distribution is continuous, it is then possible to determine the fraction of the total number of observations falling between two points with the equation

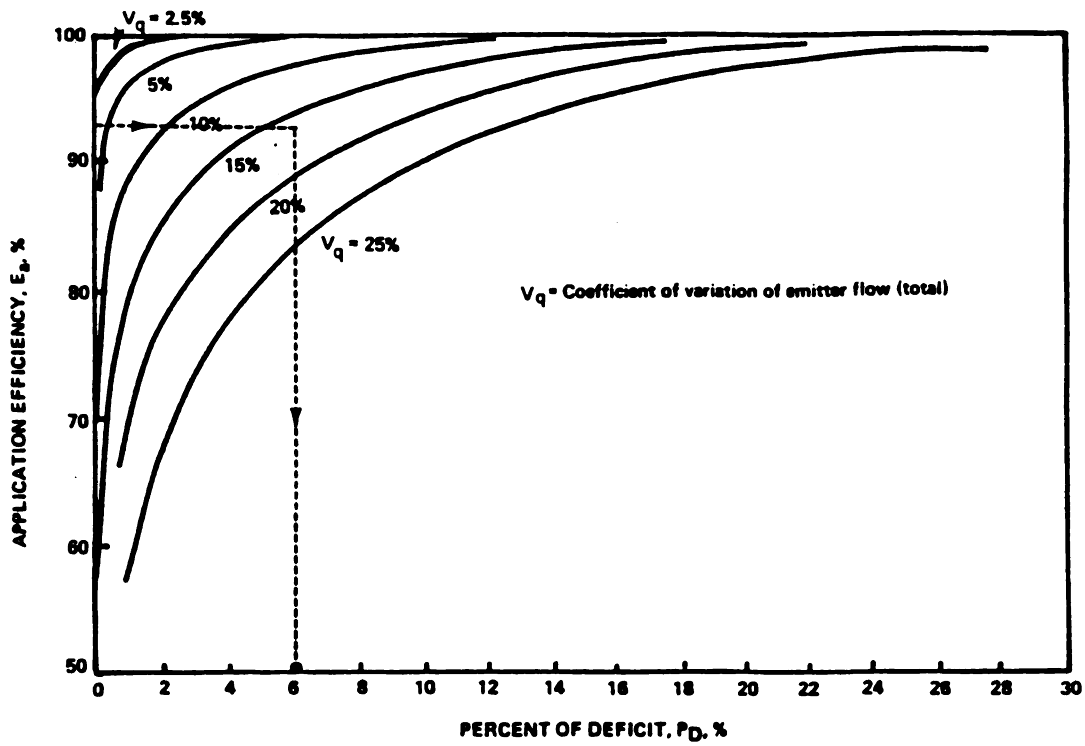

Figure 5. Application Efficiency, Coefficient of Variation and Percent Deficit Relationships (Bralts, 1984)

$$\Delta y = \frac{1}{s\sqrt{2\pi}} \int_{\alpha}^{\beta} e^{-\frac{1}{2}\left\{\frac{x - \bar{x}}{s}\right\}^2} dx$$

Substitution into this equation allows the definition of a distribution coefficient. Replacing Δy with a, α with xH_a and β with ∞, the equation becomes

$$a = \frac{1}{s\sqrt{\pi 2}} \int_{\bar{x}H_a}^{\infty} e^{-\frac{1}{2}\left\{\frac{x - \bar{x}}{s}\right\}^2} dx$$

where a is the fraction under a normal curve from $x = \bar{x}H_a$ to $x = \infty$, xH_a is the minimum application on the area a, and H_a is the fraction of the mean application ($\bar{x}$) equaled or exceeded over the area a. This equation thus may be used to determine the fraction of irrigated area in excess or deficit.

C. Irrigation Uniformity and Yield

Irrigation uniformity is related to crop yield through the effects of over and under watering. Insufficient water leads to high soil moisture tension, plant stress and reduced yields. Excess water may also reduce crop yields due to nutrient leaching and lack of root aeration.

Irrigation uniformity is also related to the efficient use of agricultural resources. Over watering implies the wasting of the energy used to power the pump and used to manufacture the chemicals which are leached below the rootzone. In deficit water areas, the inability to achieve potential crop yields results in the waste of agricultural inputs applied in anticipation of maximum yield (Gurovich et. al. 1983).

Howell (1964) showed that for theoretical cases when determining the relationship between non-uniformity and yield, if the yield relationship can be expressed as a polynomial function of application depth, the relevant characteristics are the moments of the distribution taken to the order of the polynomial. If the yield relationship is parabolic, only the mean and standard deviation are required to estimate total yield. If the relationship is cubic, then mean, standard deviation and skewness are required. If quartic, the mean, standard deviation, skewness and kurtosis are all required.

Varlev (1976) following the work of Howell, described a coefficient of non-uniformity which characterizes both non-uniformity and the yield depression caused by it. This coefficient can be used to in comparing the quality of different technologies for irrigation with respect to non-uniformity. He notes that in a large number of cases, the relationship of infiltrated water-yield can be expressed as a second degree polynomial. The coefficient of non-uniformity relates linearly for the absolute and relative yield loss due to the non-uniform distribution of the same amount of water.

Stern and Bresler (1983) investigated the relationship between crop yield and uniformity of water application. The relationship between uniformity of water applied by sprinklers, variability of soil of soil water content after irrigation and its effect on yield was studied and the yield response of sweet corn on two plots was quantitatively evaluated. The relationships among net water application, seasonal average soil water contents (before and after irrigation), depth of water measured in cans during four different irrigations and three different yield components were obtained by calculating the correlation coefficients between each pair of variables. Using normal distributions to characterize the probability density function of water application and Christiansen's coefficient to express uniformity, relative crop yield was expressed as a function of CU and total amount of irrigation water.

Seigner (1978) proposed a method of calculating the mean yield of a non-uniformly irrigated field and then illustrated the effect of non-uniform water application and the price of water on farm profits. Using cotton as an example with varying uniformities and water prices, two regions are identified. The first is associated with low water prices and high uniformities. Within this region, a reduction in uniformity justifies increased water application. Within region two, associated with high water prices and low uniformities, the opposite is true.

Amir and Seigner (1985) quantified the benefits to a producer from improved trickle irrigation emitter uniformity. The general approach is the same as that proposed by Seigner (1983). By determining the optimal seasonal water application depth and evaluating net income per unit area for a given crop, the value of improved emitter uniformity can be assessed.

Feinerman et. al. (1983) evaluated the economic implications of non-uniform water application. Two different water production functions, one for crops sensitive to excess water and the other for crops which are not sensitive to water applications greater than that required for maximum yield, are linked to a simplified water balance equation and to an economic optimization model. In the case of crops which are sensitive to excess water, productivity and optimal levels of water application are lower in non-uniform fields than in uniform fields. Where crops are not sensitive to excess water, the outcome depends on the price of water relative to crop income.

Letey et. al. (1984) describe a methodology for analyzing the effects of infiltration uniformity on crop yield, optimum application depth and profit. The relationships between corn grain yield and average applied water were presented for various uniformities of water. Generally, production at almost any water application rate was found to decrease with decreasing uniformity. Because of the nature of the crop production for corn (i.e. corn seems to be insensitive to excess water application) increased water application may substitute for uniformity. If sufficient water is applied, maximum yields may be achieved even at very low uniformity levels. However, it should be noted that the study does not account for cost associated with nutrient leaching when excess water is applied.

Solomon (1983) provides a paradigm for uniformity and yield study. He notes that most common uniformity and efficiency measures are imbued with some degree of physical significance and the steps used in calculating these measures to some extent parallel those used to calculate yield. Solomon advocates the use of distribution models rather than simply working with raw uniformity data, for reasons of generalization, and ease of estimation and computation. In selecting the proper distribution model, statistical moments must be considered the key characteristics of that distribution. Thus moment matching is the proper approach for model selection. For polynomial yield functions, crop yields are completely determined by the moments of the irrigation distribution. Thus distribution models should be fitted to empirical sprinkler data by choosing parameter values that cause the moments of the model to match the moments of the data. Although somewhat complex, Solomon recommends the use of the beta distribution model which allows the matching of the mean, standard deviation, skewness and kurtosis statistical moments. For some distributions, the first two moments may be sufficient. However, sprinkler distribution skewness and kurtosis may have a sizable effect on yield.

Guronovich and Duke (1984) provide a methodology for assessing the economic implications of improving center pivot uniformities. Using a geostatistical approach to characterize uniformity, results were then applied to the PLANTGRO simulation model developed by Hanks (1974). Because PLANTGRO only accounts for yield loss due to insufficient water, the authors assumed that each cm. of water applied over the requirement leached 13 kg./ha. below the rootzone reducing yield by 170 kg./ha. The authors conclude that the cost of installing pressure regulators at each sprinkler nozzle may be more than offset by increased uniformity and resultant increased yields.

Solomon (1984) proposed that in some special cases, irrigation uniformity measures which are generally considered quantitative indices without physical significance, may be used to determine relative yields. In situations where effective rainfall exceeds the water requirement threshhold, the Christiansen's Uniformity Coefficient appears to be the lower bound on the relative yield.

D. Computer Modeling of Maize Growth and Water Use

1. Maize Growth Simulation Models

Maize growth simulation models rely on the principle that plant growth is a response to various environmental factors. These factors and associated responses may be stated in mathmatical language. Plant growth results from the influence of various daily inputs into a system (i.e. the plant) which itself is continuously changing. The process of computer simulation is essentially estimating these daily inputs and modeling the plant growth response according to empirically derived rules.

Crop growth simulation models generally fall into two categories, incremental and decremental. Incremental models estimate crop growth from germination forward over the growing season. Decremental models begin with an optimum curve and estimate decreased production according to type, timing and duration of various stresses.

Crop growth simulation models have proven very useful in the evaluation of water management strategies. A properly formulated and validated crop model allows for testing and experimentation with irrigation depth and scheduling strategies which could take years to accomplish in the field.

Many growth simulation models have been developed and used to evaluate different farm management strategies. The purpose of this section is to provide an overview of some of the more important maize growth simulation models.

SIMAIZ developed by Duncan (1975) simulates the growth, development and final grain yield of maize over a growing season. The required initial inputs to the SIMAIZ model include certain known or inferred characteristics of the corn variety being grown, soil moisture characteristics, and management details such as planting rate, irrigation dates and amounts. Daily inputs to the model include solar radiation, maximum and minimum temperature, pan evaporation and rainfall. SIMAIZ estimates growth by modeling photosynthesis and the quantity and partitioning of the net photosynthate produced each day.

Childs et. al. (1977) developed the maize growth model CORNGRO which was later modified by Tscheschke and Gilley (1979). CORNGRO simulates maize growth and yield as affected by water stress. The major process simulated by CORNGRO are soil water movement, photosynthesis, and respiration.

The PLANTGRO model was developed by Hanks in 1974. PLANTGRO assumes that the ratio of actual to potential dry matter yield is directly related to the ratio of actual to potential transpiration. PLANTGRO is simple and inexpensive to run on a computer to determine seasonal yields as influenced by irrigation, rainfall and soil water storage.

CERES-Maize is a daily incrementing simulation model of maize growth, development and yield. CERES-maize is available in two versions; the standard, which simulates the effects of genotype, soil properties and weather on growth and in a nitrogen version which models the growth and yield effects of soil and plant nitrogen on the crop. In order to accurately determine maize growth, development and yield, the model simulates such physical and biological processes as phenological development, growth of leaves and stems, biomass accumulation and partitioning, soil water balance and plant water use, and soil nitrogen transformations. See Appendix B. for more information on file structure and validation of CERES-Maize.

2. Computer Modeling of Crop Water Use

The amount of irrigation water required by a crop is influenced by several factors, the most important of which include (1) climate, (2) available water supply or soil moisture, (3) plant growth characteristics, and (4) cultural practices (Bureau of Reclamation). The purpose of this section is to provide a brief overview of direct and indirect methods of estimating crop water use for irrigation scheduling.

a. Direct Methods

Direct methods for determining soil wetness and timing of irrigation include (1) gravimetric sampling, (2) neutron scattering, and (3) tensiometer. Gravimetric sampling involves the removal of a sample by augering into the soil, weighing the moist sample, drying and then reweighing. Soil moisture content is calculated as (Hillel, 1982).

$$w = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}}$$

Neutron scattering was developed in the 1950's and has gained widespread acceptance as method of soil moisture determination which is less laborious, more rapid and less destructive than gravimetric sampling. Neutron scattering operates by inserting a probe into a vertical access tube in the soil. The probe contains both a source of fast neutrons and a detector of slow neutrons. As these fast neutrons collide with hydrogen atoms from water in the soil they are slowed. The slow neutrons are counted and soil water content is determined by matching this reading to a calibration curve. Although neutron scattering is a convenient way of making soil water determinations, it has some disadvantages including high initial instrument cost and danger associated with exposure to neutron radiation.

The tensiometer is comprised of a porous ceramic cup, filled with water and connected to a manometer. As the cup encounters the surrounding soil, the water inside tends to equilibrate with the surrounding soil water. As the water is drawn out of the cup by soil matric forces, a drop in hydrostatic pressure occurs which is indicated by the manometer reading.

b. Indirect Estimates of Soil Water

The principal techniques used to estimate ET or water use, are based completely or in part on measurements of (1) solar radiation (2) wind (3) temperature, and (4) humidity. The best known ET estimation method requiring only temperature data is the Blaney-Criddle equation (1950). This equation, although easy to solve, does not work well in humid regions.

Jensen and Haise (1963) developed an equation which estimates ET based on inputs for both temperature and radiation. This equation has been found to work well in the central U.S, however it does not correlate well in other regions.

The Penman equation (1948) combines net radiation terms with advective energy transfer effects on crop use into one equation. The Penman equation, modified for estimating alfalfa based reference ET, is

$$E_{tr} = \frac{\Delta}{\Delta + \gamma} (R_n + G) + \frac{\gamma}{\Delta + \gamma} 15.36\ W_f\ (e_a - e_d)$$

where E_{tr} = reference crop ET in cal/cm^2*d; Δ is the slope of the vapor pressure - temperature curve in mb/deg. C; γ is the psychrometer constant in mb/deg. C; R_n is net radiation in cal/cm^2*d; G is soil heat flux to the surface in cal/cm^2*d; W_f is the wind function (dimensionless); $(e_a - e_d)$ is the mean daily vapor pressure deficit in mb; and 15.36 is a proportionality constant in cal/cm^2*d*mb.

The Penman equation has been found to be very accurate for ET estimation in a wide variety of climatic conditions (Jensen, 1983)

c. Computerized Irrigation Scheduling

The purpose of irrigation scheduling is to provide farm managers with accurate information on soil water status. With this information, irrigators are able to make better decisions as to the timing and volume of irrigation water application. SCHEDULER (Driscoll and Bralts, 1986), like most scheduling software, uses a "checkbook" accounting system. Climatic data, antecedent soil moisture, rainfall, and irrigation are entered into the program on a weekly basis. SCHEDULER then uses the Penman equation to calculate ET and subtract these losses from the initial soil moisture. Irrigation and rainfall volumes are added to this value so that a new soil moisture content is calculated. See Appendix B. for additional information on SCHEDULER.

E. Summary

1. The definition of irrigation uniformity may be approached from either a distribution modeling perspective or by a uniformity definition. Although distribution models may in some cases be more representative of system uniformity, their complexity makes them quite difficult to implement in an on-farm evaluation procedure. Christiansen's Uniformity Coefficient is the most popular expression of sprinkler uniformity, however it has been justly criticized as arbitrary. Therefore in the interest of simplicity and accuracy, the Wilcox and Swailes coefficient (coefficient of variation) will be used in this report, to express uniformity of irrigation and yield.

2. Most of the work on the relationship between irrigation uniformity and yield has been of a theoretical nature. There is a need for a better understanding of how irrigation uniformity affects yield and how mitigating factors such as seasonal rainfall may influence seasonal uniformity.

3. Several maize growth models are presently available and could possibly be used in the type of analysis proposed here. The CERES-Maize growth simulation model in the

standard and nitrogen version is more encompassing than some of the other models reviewed, requires easily attainable input information, and has been validated in a variety of climates. (Jones and Kiniry, 1986). Thus the CERES-Maize model will be used in this study.

4. Computerized irrigation scheduling with software such as SCHEDULER facilitates accurate estimation of soil moisture status and allows for better decision making in timing and volume of irrigation application. Thus, SCHEDULER will be used in this study, for determining the effect of irrigation scheduling and uniformity on yield.

III. METHODS

The review of literature has shown that a large body of theoretical work exists dealing with the issues of irrigation uniformity and crop yield. There is, however, a lack of empirical research in this area. In addition, previous research has not effectively focused on how rainfall affects the seasonal uniformity of water application. More accurate estimates of the effects of irrigation uniformity on crop yield and better understanding of seasonal water application uniformity when rainfall is considered may aid irrigators in making more economically sound management decisions where irrigation is concerned.

A. Research Approach

Based upon the need to gain further insight into irrigation uniformity as it affects irrigators in humid regions, the following approaches are proposed to achieve the stated research objectives.

Objective 1: To evaluate the mean and variance of maize yield with respect to high, medium and low center pivot irrigation system uniformities.

Approach

Eight center pivot irrigation systems, exhibiting a range of uniformities, which either have been evaluated by SCS in St. Joseph County, or which have been generated will be selected for yield and uniformity evaluation. Using historical weather data from 1984 collected at the Kellogg biological station, in Kalamazoo, Michigan, a mean application rate of 19.00 mm (.75 in) will be scheduled with the SCS SCHEDULER software program. Three schedules will be generated with irrigations beginning at 40, 50, and 60 percent soil moisture depletion. Collector data from the SCS evaluations will be adjusted so that the mean application rate will equal 19 mm as specified by the schedule.

After the collector values are adjusted, each of these values for each system will be entered into the CERES-Maize irrigation file for an individual run. All other inputs (i.e. soil type, corn variety, weather, planting date etc.) except depth of water applied at each irrigation will be kept constant. Mean, standard deviation and coefficient of variation will be calculated for the water distributions and resultant yields as estimated by CERES-Maize. Coefficient of variation of yield and mean yield will be analyzed with respect to irrigation water applied and gross water applied. The effect of scheduling on irrigation water requirement and yield will also be analyzed.

Objective 2: To determine the effect of rainfall on the uniformity of irrigation systems and on the uniformity of crop yield.

Approach

During this stage of the analysis, the procedure outlined in objective 1 will be followed, except rainfall will be eliminated from the weather data. In addition, a theoretical basis will be presented for the determination of an adjusted coefficient of variation considering rainfall. The resultant uniformities in crop yield will be compared with those generated under rainfall and the adjusted coefficient of variation will be verified.

Objective 3: To analyze and discuss the effects of these new insights into irrigation uniformity on economics and management decisions.

Approach

Costs of irrigation (water and energy) and yield loss, will be found or estimated and used to analyze and discuss the economic effects of irrigation non-uniformity.

Specific issues to be addressed are:

1. The costs and returns of different scheduling strategies for varying uniformity levels.

2. The effects that substantial amounts of seasonal rainfall may have on the decisions to improve or replace center pivot irrigation systems.

B. Research Methods

1. Objective 1. Method

Eight center pivot uniformities, with CVs ranging from 0 to .58 were evaluated. Five of these uniformities were based on actual center pivot evaluations carried out from 1983-86 by the Soil Conservation Service in St. Joseph County, Michigan. See Appendix A for the center pivot evaluation procedure used by SCS. The collector values for three of the evaluations were generated using a random number generation procedure. Generated uniformities were necessary in order to evaluate a complete range of CVs. Once actual and generated catch can data were assembled, each evaluation was entered into a short Turbo-Pascal program written by the author. Given inputs for the can weighting factor and the depth of water in the can in mm, the program calculates values for mean depth of application, variance of application depth, coefficient of variation and Christiansen's Uniformity Coefficient. See Appendix C for the listing of this program. It was decided that irrigation would be scheduled based on a mean application depth of 19.00 mm (.75 in). In order to avoid generating an irrigation schedule for each system, catch can values were adjusted so that the CV remained the same for the system but mean depth of application was equal to 19.00 mm. The adjustment was made using the following equation

$$19.00 * \text{original depth} / \text{original mean} = \text{adjusted depth}.$$

After the adjusted catch can values were calculated, the system evaluation data were again entered into the computer program to verify that the adjustments were correct (i.e. that the new mean = 19.00 mm and that the adjusted CV = the original CV).

Irrigation scheduling was accomplished with the SCHEDULER software program using 1984 weather data collected at the Kellogg Biological Station near Kalamazoo, Michigan. Sample input for the SCHEDULER program is presented in Figure 6 . The soil type used in both SCHEDULER and CERES-Maize was a Spinks Loamy Sand soil. This soil was selected because it is one which is commonly irrigated in the state of Michigan and because, given its coarse texture, lateral water movement is minimal. Characteristics of the Spinks soil series are presented in Table 1 .

Table 1 . Spinks Series Soil Characteristics

Depth mm (in)	USDA Texture	AWC mm/mm	(in/in)
0 - 254 (0-10)	loamy sand	.11	(.11)
254 - 660 (10-26)	loamy sand	.11	(.11)
660 - 1524 (26-60)	sand	.07	(.07)
Rootzone 914 mm (36 in)		88.90 mm	(3.5 in)

Pioneer commercial corn variety 3780 was selected for the CERES-maize analysis. It was determined that this variety had an approximately 120 day growing season. This value was then used as input for SCHEDULER. Three different schedules were generated with the SCHEDULER program. The first schedule initiated irrigation when 40% of the available water was depleted; the second, when 50% of the water was depleted and the third when 60% of the available water was depleted from the soil profile. It should be noted here that the crop rooting depth was assumed to be .91 m (3 ft.) for scheduling and for the analysis with CERES - Maize. A summary of these irrigation schedules is presented in Table 2 and graphically in Figure 7.

```
01.   COUNTY?  ST. JO
02.   FARM NAME?  SALLY 1
03.   CROP TYPE?  CORN
04.   GROWING SEASON (DAYS) ?  120
O5.   SOIL MOIST. HOLDING CAPACITIES (IN/FT)
                          FOR 1 FOOT  ?  1.32
                          FOR 2 FOOT  ?  1.32
                          FOR 3 FOOT  ?   .84
06.   MINIMUM SOIL MOISTURE BEFORE IRRIGATION EXPRESSED
      AS A PERCENTAGE OF AVAILABLE PROFILE CONTENT? 50
07.   DATE OF PROFILE MOISTURE CONTENT  5.24
08.   PROFILE MOISTURE CONTENT ESTIMATE (PERCENT) ON 5.24? 85
09.   RAIN SINCE 5.24     (IN)  :5.27   0.01
                                :5.29   0.10
                                :0.00   0.00
                                :0.00   0.00
                                :0.00   0.00
10.   IRRIGATION WATER SINCE 5.24
                                :0.00   0.00
                                :0.00   0.00
                                :0.00   0.00
                                :0.00   0.00
                                :0.00   0.00
11.   EMERGENCE DATE 5.10
12.   NET WATER PER IRRIGATION CYCLE (INCHES) .75
13.   TYPE IN DATE DESIRED AS MO.DY.YR  5.30.84
```

Figure 6. Sample Input for Scheduler

Table 2. Irrigation Scheduling and Crop Growth Summary (With Rainfall)

	MAY				JUNE				JULY				AUG.				SEPT.			
	RAIN	IRRIG. (MM)			RAIN	IRRIG. (MM)			RAIN	IRRIG. (MM)			RAIN	IRRIG. (MM)			RAIN	IRRIG. (MM)		
DATE		40	50	60		40	50	60		40	50	60		40	50	60		40	50	60
1														19		19	7.87			
2										19					19		.51			
3														Begin						
4									.25		19			Grain Fill			3.3			
5					.25							19								
6						End Juv.			3.8							19	.25			
7					1.5	Stage				19				19						
8															19		9.14			
9					1.0				27.9									End Grain		
10		Emergence							16.0							19	14.22	Fill		
11									8.4					19				Physiol.		
12					1.3	19									19			Maturity		
13	6.1					Tass. Init														
14							19									19				
15																				
16								19						19						
17					.25										19					
18	10.9					19				19										
19	1.8										19					19				
20	2.5						19		13.5											
21	31.8								.25					19						
22	1.8				.76	19		19		Silking					19					
23									.51											
24							19		6.1							19				
25	.25								.51											
26	.25					19			1.0			19		19						
27					1.0					19			1.52		19					
28																				
29	16.8						19	19			19									
30													10.41							
31																				
TOTAL	72.2				6.06	76	76	57	78.22	76	57	38	11.93	114	114	114	35.29			

TOTAL RAINFALL = 215.63 MM (8.49 IN)

TOTAL IRRIGATION

40% DEPLETION SCHEDULE = 304.00 MM (10.50 IN)

50% DEPLETION SCHEDULE = 285.00 MM (9.75 IN)

60% DEPLETION SCHEDULE = 266.00 MM (9.00 IN)

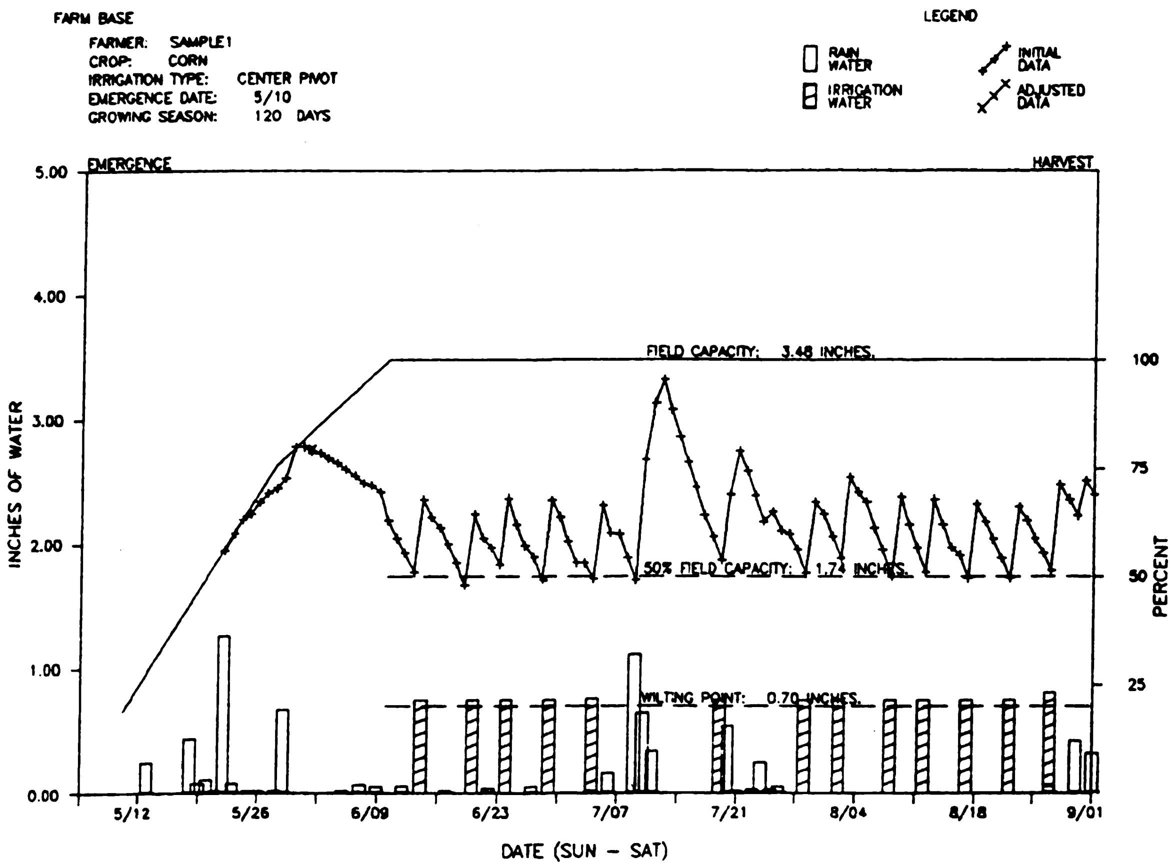

Figure 7. Irrigation Scheduling Summary Graph (with Rainfall)

The irrigation dates generated by SCHEDULER were entered into three separate irrigation files in the standard version of the CERES-Maize corn model. See Appendix B for information on inputs and file structures for CERES-Maize. The same weather data (1984 KBS) were entered into the CERES-Maize weather files. It should be noted here that the CERES-Maize model calculates ET using daily climatological inputs of maximum temperature, minimum temperature, total solar radiation and rainfall. In addition to these inputs, SCHEDULER requires inputs for maximum and minimum relative humidity , night time wind speed and average wind speed. Despite these differences, Bralts and Algozin (1985) have found that the ET estimates for the two methods are quite similar. Table 3 presents a comparison of lysimeter, SCHEDULER, and CERES-Maize evapotranspiration estimates.

Table 3 . Average ET Estimates from SCHEDULER and CERES-Maize Compared to ET Measured by Lysimeter

Period (1985)	Lysimeter (mm/day)	SCHEDULER (mm/day)	Ceres-Maize (mm/day)
6/10 - 7/10	3.91	4.83	3.83
8/04 - 8/18	4.06	3.35	3.25
Average	3.99	4.09	3.53

(Bralts and Algozin, 1985)

After irrigation scheduling was completed and other parameters for CERES-Maize were determined, each irrigation depth at each observation point was entered into the irrigation files for the model. See Figure 8 for sample input for, and Figure 9 for sample output from CERES-Maize.

When the model runs were completed, coefficient of variation of yield and mean yield for each uniformity were determined. See Appendix C for the yield results for each uniformity evaluation.

2. Objective 2. Method

a. Theoretical Development

As noted in the review of literature, the normal distribution has been considered by a large number of researchers. Most authors have found that this distribution provides an adequate representation of irrigation data over a wide range of uniformities, sprinkler sizes and spacings. Another advantage of using the normal distribution is its simplicity. Only two statistical moments, mean and standard deviation, are required to describe the distribution.

Uniformity measures are calculations based on estimates of irrigation depths at various locations in an irrigated area. Using these depths, a single number is produced which may serve as an indicator of uniformity of water applied by an irrigation system. Uniformity

```
PLEASE INPUT THE NUMBER CORRESPONDING TO THE PARAMETER YOU WISH TO CHANGE.

ENTER ZERO (0) IF NONE.

1. WEATHER FILE =  KBSWET.DAT              13. INITIAL SW CONDITION =   .9
2. GENETICS FILE =  CGENET                 14. DATE OF SOWING = 115 0
3. SOILS FILE =  SOIL.JOE                  15. SOWING DEPTH =  5.0
4. IRRIGATION DATA (Y/N/A) =  Y            16. PLANTS/M**2 =   7.2
5. IRRIGATION FILE =  CIRRIG.DAT           17. DATE OF SILKING =   0
6. INITIAL SW FILE =  SWATER               18. DATE OF MATURITY =   0
7. BIOMASS OUTPUT FILE = BOCORN            19. GRAIN YIELD (KG/HA) =      0.
8. WATER OUTPUT FILE =  WACORN             20. GRAIN WIEGHT (DRY) =   .00
9. FREQUENCY OF OUTPUT = 10                21. GRAINS/M**2 =      0.
10. THE CROP VARIETY =   24                22. GRAINS/EAR =    0.
11. THE SOIL NUMBER =  166                 23. MAXIMUM LAI =    .0
12. THE LATITUDE =  42.0                   24. BIOMASS (GRAMS/M**2) =     0.
```

Figure 8. Sample Input for CERES-Maize

```
VARIETY NUMBER   24  VARIETY NAME  PIO 3780

LAT =42.0 , SOWING DEPTH = 5.0 CM , PLANT POP =  7.2 PLANTS/M**2

GENETIC CONSTANTS  P1 =170.  P2 =.76  P5=685.  G2 =600.  G3 =10.
SOIL ALBEDO= .14  U= 6.0  SWCON= .90 RUNOFF CURVE NO.=67. SOIL NO.=166

JULIAN DAY     IRRIGATION(MM)
     168          23.
     174          23.
     178          23.
     183          23.
     188          23.
     208          23.
     214          23.
     219          23.
     223          23.
     227          23.
     232          23.
     237          23.

 DEPTH-CM        LOW LIM    UP LIM    SAT SW    EXT SW    INIT SW     WR

  0.-    10.      .059       .171      .221      .112      .160     1.000
 10.-    30.      .059       .171      .221      .112      .160      .800
 30.-    45.      .061       .173      .223      .112      .162      .300
 45.-    61.      .056       .168      .218      .112      .157      .090
 61.-    76.      .056       .127      .177      .071      .120      .040
 76.-    91.      .041       .112      .162      .071      .105      .009

         91.4      5.1       14.0      18.6       9.0      13.1  TOTAL PROFILE

       THE PROGRAM STARTED ON JULIAN DATE   92

        JUL   CUM                                         WATER BALANCE COMPONENTS
 DAY    DAY   DTT   PHENOLOGICAL STAGE  CUMULATIVE          AFTER GERMINATION

 4/24/ 0 115    0.  SOWING              BIOMASS   LAI      CSD1  ET   PREC PESW
 4/25/ 0 116    3.  GERMINATION                                  25.  40.   8.1
 5/10/ 0 131   47.  EMERGENCE                                    22.  15.   7.1
 6/ 6/ 0 158  182.  END JUVENILE STAGE    11.     .26       .00  73.  88.   6.8
 6/13/ 0 165  289.  TASSEL INITIATION     46.     .83       .00  94.  92.   4.0
 7/21/ 0 203  764.  SILKING, LNO= 19.0 1054.    4.95       .00 271. 279.   5.0
 8/ 3/ 0 216  934.  BEGIN GRAIN FILL    1399.    4.57       .00 322. 333.   5.2
 9/ 8/ 0 252 1420.  END FILL, GPP=452. 2645.    1.16       .00 502. 504.   4.2
 9/10/ 0 254 1444.  PHYSIO MATURITY     2645.    1.16

                           PREDICTED VALUES     MEASURED VALUES

SILKING   JD                     203                0
MATURITY JD                      254                0
GRAIN YIELD  KG/HA (15)        12691.               0.
KERNEL WEIGHT  G (DRY)          .3293             .0000
FINAL GPSM                      3256.               0.
GRAINS/EAR                       452.               0.
MAX. LAI                         4.95              .00
BIOMASS  G/SM                   2645.               0.
```

Figure 9. Sample Output from CERES-Maize

measures are only a function of the variation of irrigation depth, although weighting factors are sometimes used to express a greater degree of significance of some (usually lesser) depths.

Statistical Parameters

Several different measures have been used to describe the uniformity of irrigation application including Christiansen's Uniformity Coefficient (CU) and the Wilcox and Swailes Coefficient or Coefficient of Variation (CV). CV was introduced as a method of uniformity evaluation by Wilcox and Swailes in 1947. CV, which assumes that the distribution of irrigation water is normal, uses common statistical paramenters, mean and standard deviation, to estimate uniformity. The equation for CV is defined as

$$CV = \frac{S}{\overline{X}}$$

where

CV is the coefficient of variation, S is the standard deviation of the distribution of water, and $\overline{X}$ is the mean of the distribution of water measured.

In the case of center pivot uniformity evaluation, the mean is defined as the sum of the values for each observation (i.e. volume of water in each can) divided by the number of observations (number of cans). In center pivot irrigation, each can represents a different portion of the irrigated area, therefore a weight is assigned to each can volume. Thus the equation for the mean becomes

$$\bar{X}_w = \frac{w_i \, y_i}{w_i}$$

where X_w is the weighted mean water application for the system, w_i is the weight value for each observation, and y_i is the value measured at each observation.

Standard deviation is defined as

$$S = \left(\frac{(y_i - \bar{X})}{n - 1} \right)^{.5}$$

As Marek et.al. (1986) have shown, in a situation where obsevations are weighted and where the observation spacing is constant, the equation becomes

$$S = \left(\frac{\dfrac{\sum(w_i y_i 2)}{(\sum w_i - 1.0)} - (\sum w_i y_i)^2}{\sum w_i \, (\sum w_i - 1.0)} \right)^{.5}$$

where all terms are as previously defined.

Addition of a Constant

When a constant (C) is added to a distribution, the statistical moments of mean and standard deviation are affected such that $\bar{X}$ becomes $\bar{X}$ + C. Standard deviation however remains unchanged. For example, in the series of numbers 3,4,5,7,5,2, the mean is calculated as 4.33 and the standard deviation is 1.75. If a C equal to 3 is added to each of the numbers in the series, the new mean is 7.33 which equals $\bar{X}$ + C. The standard deviation remains the same.

The effect of the addition of a constant to a distribution is to increase the mean by the value of that constant while leaving the standard deviation unaffected. The coefficient of variation ($S/\bar{X}$) then, is effectively decreased due to the increase in the denominator.

Theoretical Application to Irrigation Uniformity

In arid regions where most if not all water is supplied by irrigation, a high degree of uniformity, represented by a low CV, is desirable to insure adequate crop growth over an entire irrigated area. As previously noted, rainfall is often the major source for crop water requirements in humid regions and should be taken into consideration in the evaluation the uniformity of a given irrigation system. If rainfall is assumed to be 100% uniform over an irrigated area it then represents a constant value which may be added to the mean value of the irrigation distribution. For example, if a center pivot irrigation system has a measured mean application rate of 19 mm, a standard deviation of 5.7 mm and a CV of .30 and if 50% of the seasonal water requirement is supplied by rainfall then the CV considering rainfall would be

$$CV = \frac{5.7}{19 + 19} = .15$$

or approximately 1/2 of the originally measured CV.

3. Verification Approach

During this stage of the analysis, the procedure outlined above for objective 1 was followed, except that rainfall and pre-season soil water were eliminated from the analysis. In order to allow germination to occur, the irrigation system was operated four times immediately prior to the date of planting. The irrigation schedule summary is presented in Table 4 and graphically in Figure 10. Because there was no difference in total irrigation requirement for the 50% and 60% depletion schedules, only the 40% and 50% depletion schedules were evaluated. Again, uniformity of yield and mean yield will be calculated for each irrigation system. The results of the evaluations without rainfall approximate the expected yields based on simply evaluating the uniformity of the center pivot

Table 4. Irrigation Scheduling and Crop Growth Summary (Without Rainfall)

DATE	MAY Irrigation 40	MAY Irrigation 50	JUNE Irrigation 40	JUNE Irrigation 50	JULY Irrigation 40	JULY Irrigation 50	AUG. Irrigation 40	AUG. Irrigation 50	SEPT. Irrigation 40	SEPT. Irrigation 50
1										
2						19				
3			19				19			
4					19				19	
5										
6						19		19		
7				19						
8					19		19			
9										
10			19					19		
11						19				
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17							19			
18				19		19				
19										
20					19			19		
21			19							
22						19	19			
23				19						
24					19					
25			19					19		
26						19				
27				19						
28							19			
29			19		19					
30										
31						19		19		
TOTAL	76 (Pre-Season)	76	114	95	133	152	114	114	19	0

TOTAL IRRIGATION

40% DEPLETION SCHEDULE = 456 MM (18.00 IN)

50% DEPLETION SCHEDULE = 437 MM (17.25 IN)

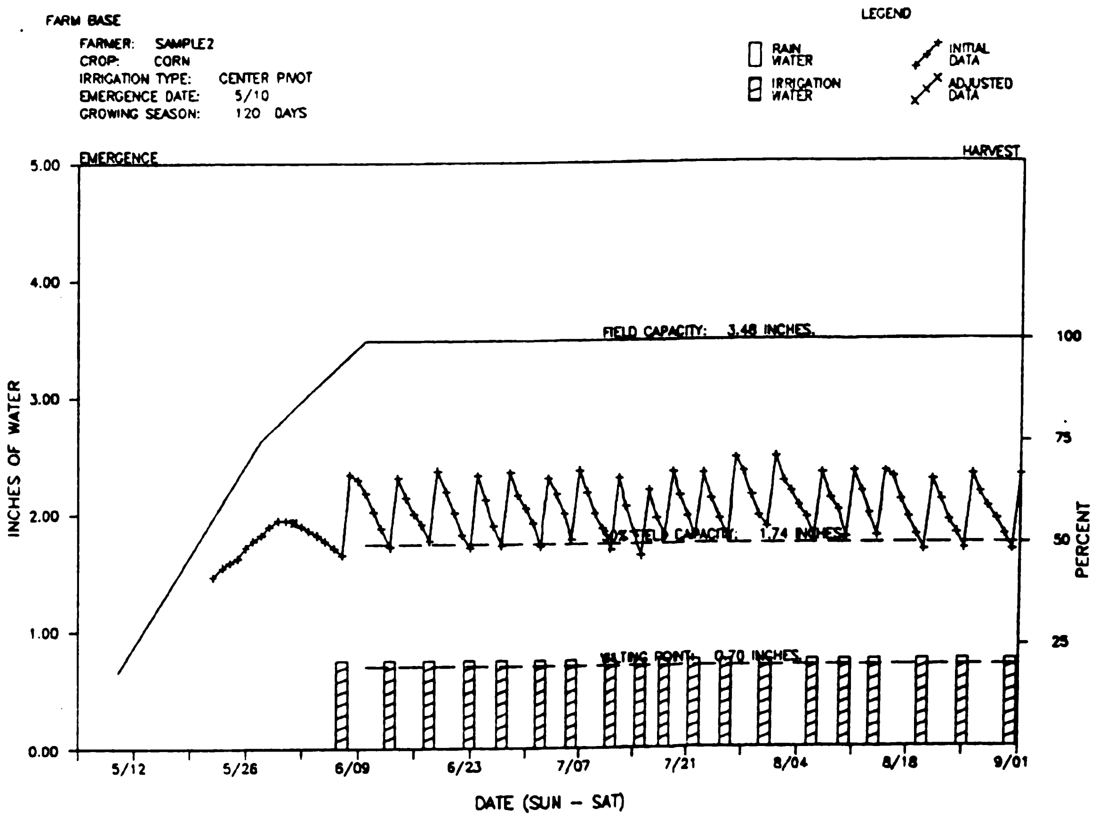

Figure 10. Irrigation Scheduling Summary Graph (without Rainfall)

system, without considering the addition of rainfall. In order to test the validity of an adjusted CV, the volume of effective rainfall (including initial soil moisture) from 1984 has been calculated . This value has been used to estimate the constant added to the mean of the systems tested. If the adjusted CV theory is indeed valid, then when the rainfall constant is added to the system CV (without rainfall) the adjusted CV should more closely express the yield CV with rainfall.

C. Analysis Techniques

Coefficient of variation of yield, mean yield and percent decrease in yield will be calculated for all schedules and uniformities. Data analysis and representation will be performed using the Plot-it statistical package. Linear regression analysis will be performed to determine the correlation between CV of yield and CV of the irrigation system application (for all schedules, with and without rainfall), mean yield and CV of the irrigation systems and percent decrease in yield and CV of the irrigation systems. The three irrigation scheduling strategies will be compared under rainfall and dry conditions.

To determine the validity of the adjustment to CV considering rainfall, the volume and percent of effective rainfall for 1984 will be calculated. This value will then be used to adjust the CV for each system.

Regression lines for irrigation CV measured vs yield with rainfall, irrigation CV measured vs yield without rain and adjusted irrigation CV vs expected yield will be compared.

Economic analysis will be carried out by estimating costs (i.e. due to yield loss) of non-uniform irrigation under different irrigation requirements. In addition, cost analysis of different scheduling strategies will be compared to determine optimal scheduling strategy with increasing irrigation costs.

IV. RESULTS, ANALYSIS AND DISCUSSION

A. Irrigation Uniformity, Yield and Scheduling

1. With Rainfall

In this part of the analysis, the CERES-Maize corn model was run under eight different irrigation uniformities (for the 40% and 60% depletion schedules) and eleven different uniformities for the 50% depletion schedule. The objective was to determine the effect of irrigation uniformity and schedule on yield uniformity and mean yield under typical rainfall conditions. Except for water applied to each sector of the field and timing of water application, all other parameters such as weather, rainfall, soil water holding capacity and maize variety have been kept constant. It was assumed in the analysis that the model provided accurate yield values for each irrigation depth and schedule.

Irrigation uniformities as expressed by CV are compared with CV of maize yield and mean yield under the three different scheduling strategies. The results for each schedule are presented in Table 5. Figures 11 through 17 show the relationships graphically.

Table 5 . Irrigation Uniformity and Yield for 40% 50% and 60% Depletion Schedules (With Rainfall)

CV OF IRRIG.	CV OF YIELD			MEAN YIELD (KG/HA)		
	% Depletion Scheduling Strategy			% Depletion Scheduling Strategy		
	40	50	60	40	50	60
0.00	0	0	0	12692	12692	12692
.17	0	0	0	12691	12688	12688
.22	-	.06	-	-	12427	-
.26	.07	.06	.09	12486	12386	12360
.29	.02	.02	.04	12635	12564	12454
.33	-	.11	-	-	12075	-
.39	.11	.12	.13	12116	12029	11926
.42	-	.18	-	-	11724	-
.44	.16	.18	.17	12080	11933	11823
.52	.20	.20	.21	11786	11677	11584
.58	.20	.20	.21	11800	11735	11532

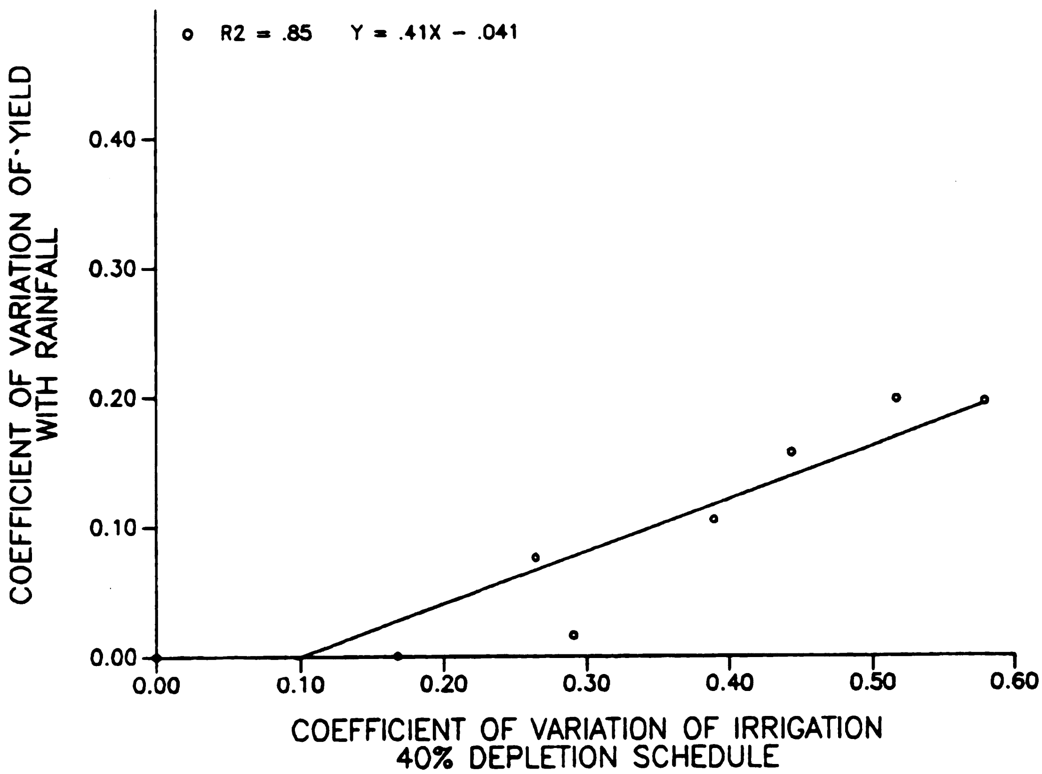

Figure 11. CV of Irrigation and CV of Yield
(40% Depletion Schedule)

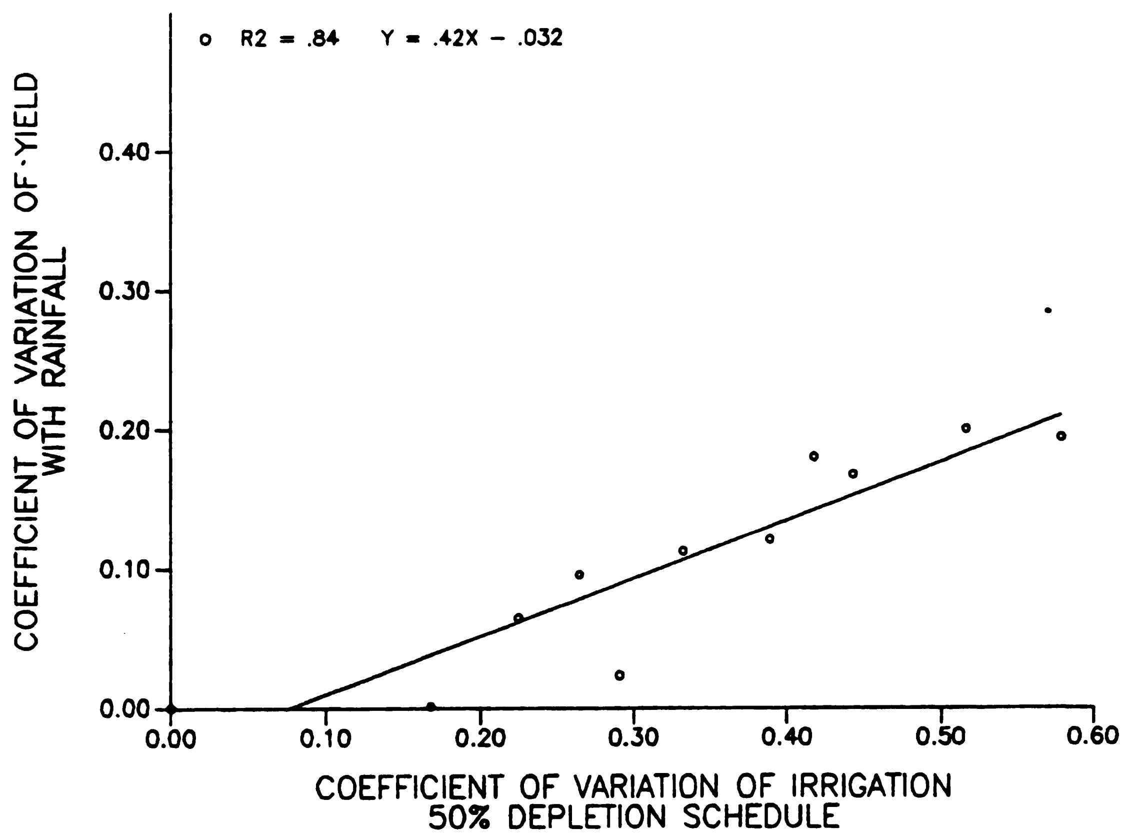

Figure 12. CV of Irrigation and CV of Yield
(50% Depletion Schedule)

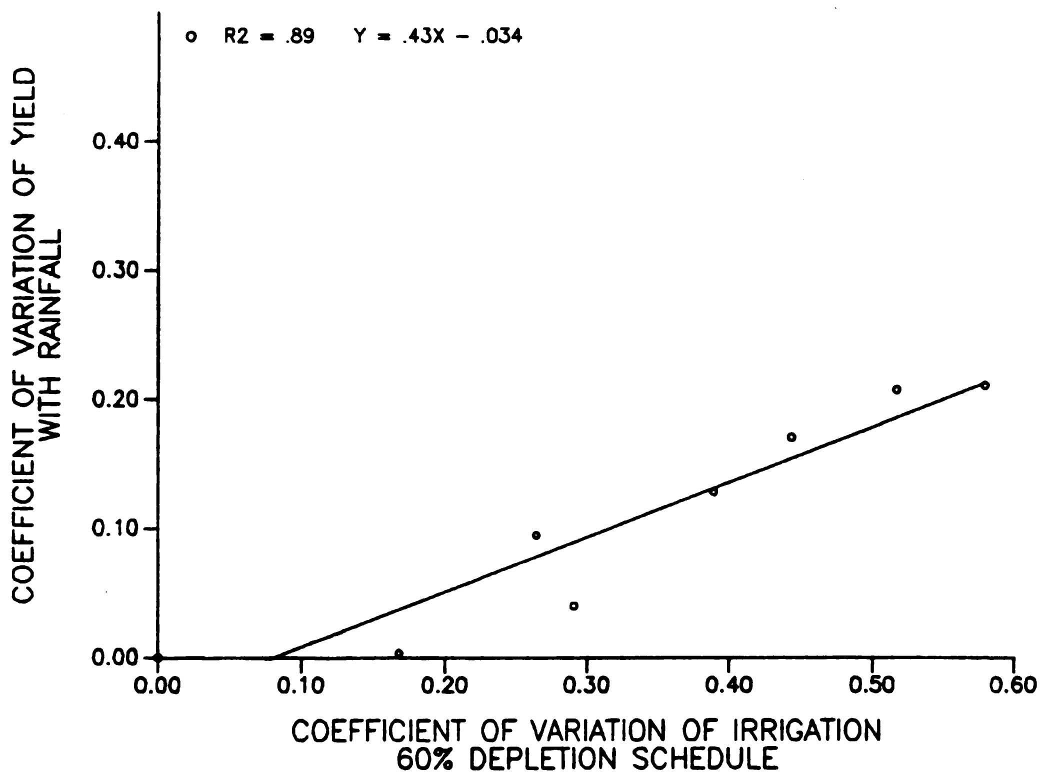

Figure 13. CV of Irrigation and CV of Yield (60% Depletion Schedule)

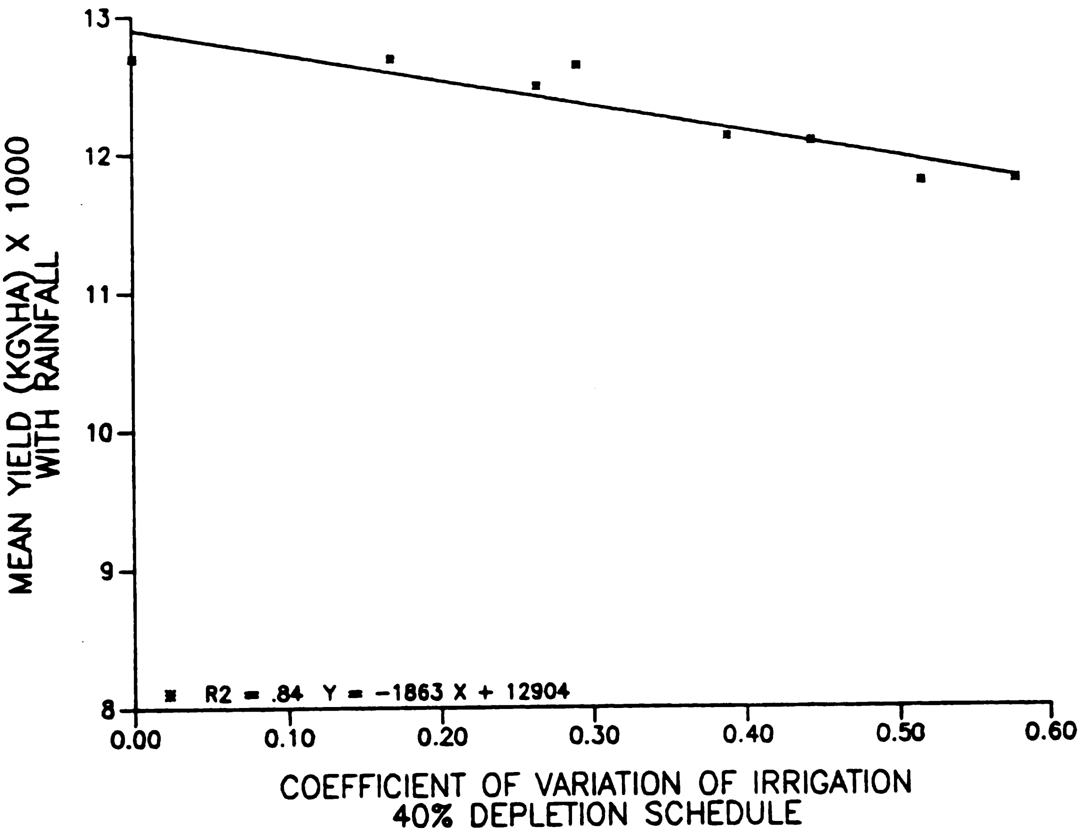

Figure 14. CV of Irrigation and Mean Yield
(40% Depletion Schedule)

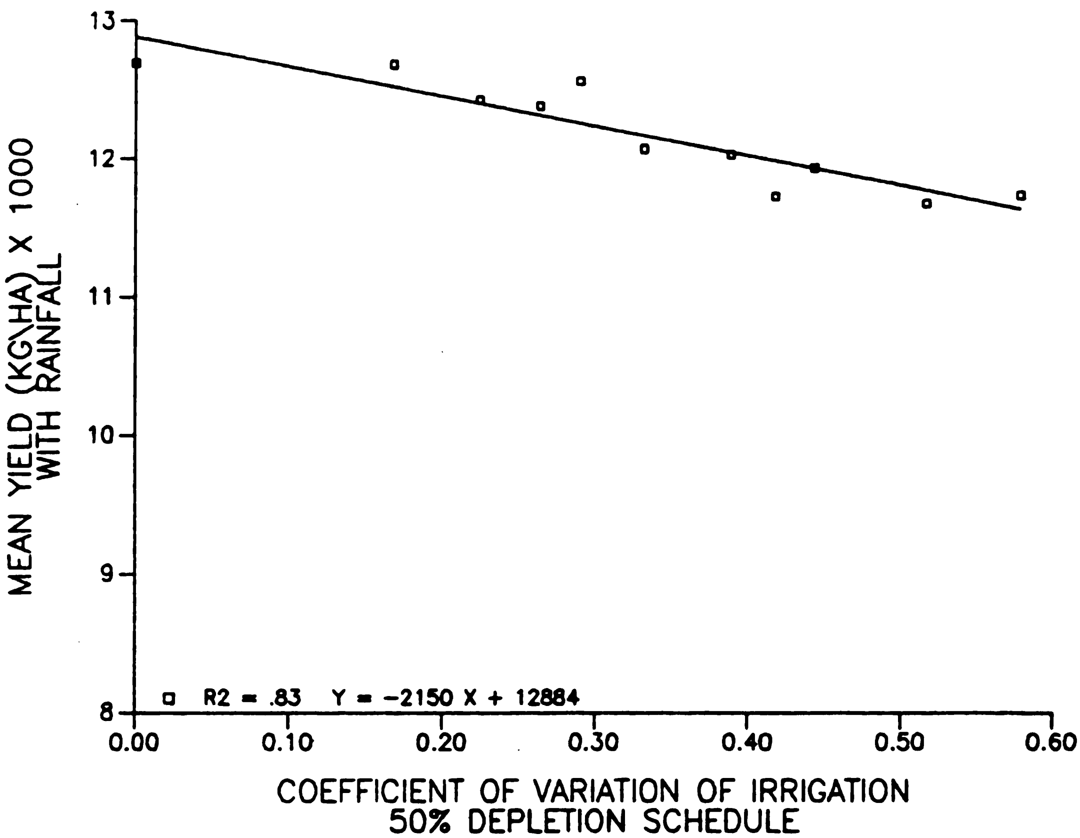

Figure 15. CV of Irrigation and Mean Yield (50% Depletion Schedule)

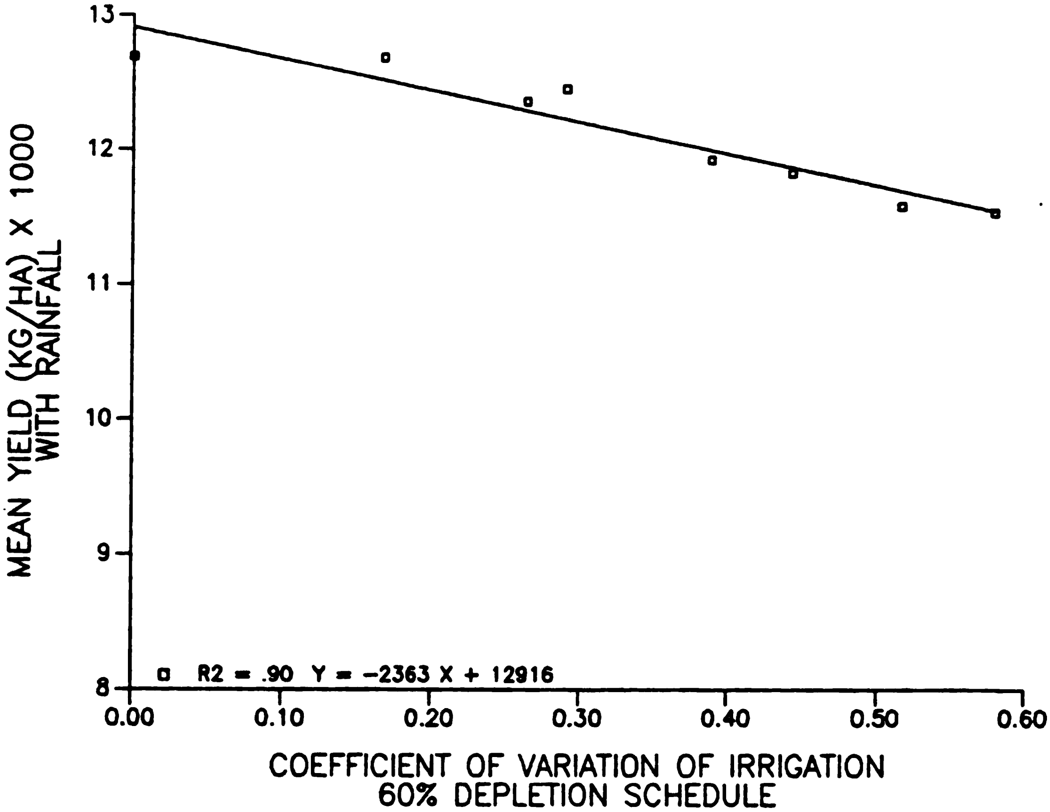

Figure 16. CV of Irrigation and Mean Yield (60% Depletion Schedule)

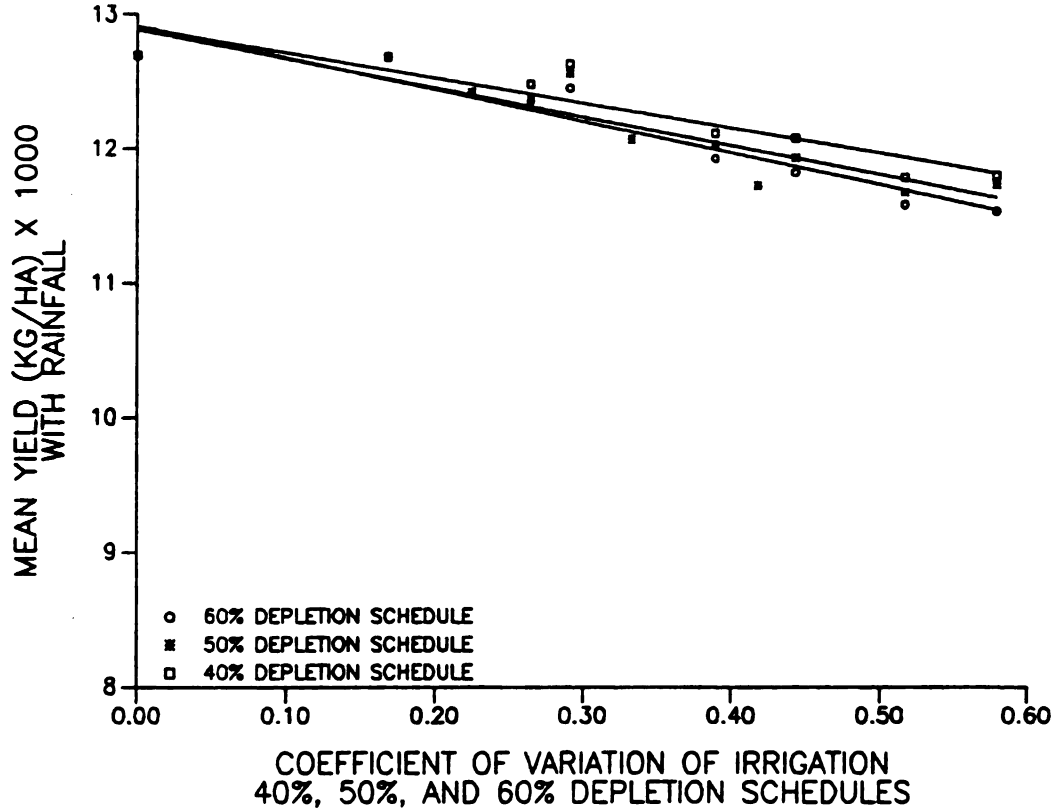

Figure 17. CV of Irrigation and Mean Yield : 40%, 50% and 60% Depletion Scheduling Comparison

From Table 5. and Figure 17, it can be seen that under the rainfall conditions analyzed here (40% of crop water requirement provided by rainfall) there is little effect on CV of yield or mean yield among the different scheduling strategies. This would then suggest that under conditions where rainfall provides more than 40% of the crop water requirement during a growing season, a conservative scheduling strategy (i.e. irrigation when 60% of the water is depleted rather than when only 40% or 50% of the available water is used) is appropriate. It should also be noted that the data and figures suggest that at very high uniformities (CV <.17) CV of yield is virtually 0, with little effect on mean yield compared with the maximum expected yield. This is probably due to the fact that at high uniformities, only the top of the parabolic maize-water production function curve is being analyzed. Figure 18 (Kramer and Jensen, 1979) on the following page is an example of a production function curve relating a single input and output.

2. Without Rainfall

The results of the CERES-Maize yield analysis performed without rainfall are presented in Table 6 and Figures 19 through 23 .

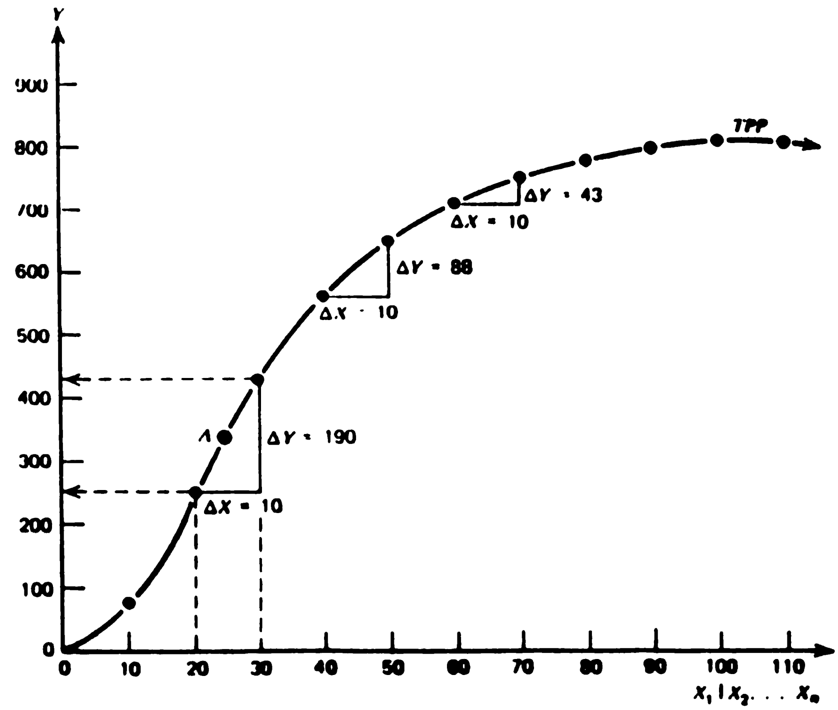

Figure 18. Parabolic Production Function Example

Table 6 . Irrigation Uniformity and Yield for 40 and 50% Depletion Schedules (Without Rainfall)

CV OF IRRIG.	CV OF YIELD % Depletion Scheduling Strategy		MEAN YIELD (KG/HA)	
	40	50	40	50
0.00	0	0	12692	12690
.17	.04	.06	12440	12278
.22	-	.32	-	11194
.26	.26	.26	11570	11396
.29	.28	.29	10896	10709
.33	-	.45	-	9997
.39	.46	.47	9820	9602
.42	-	.55	-	9176
.44	.49	.49	9392	9268
.52	.53	.52	9080	9058
.58	.54	.55	9097	8959

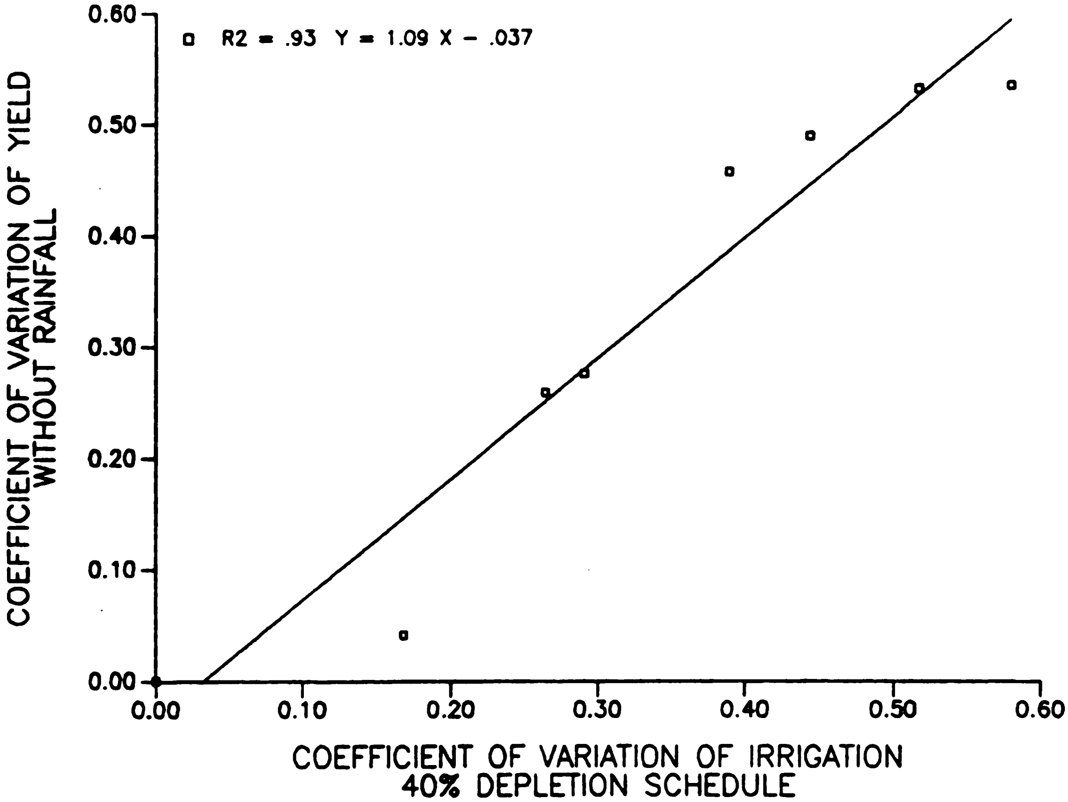

Figure 19. CV of Irrigation and CV of Yield Without Rainfall (40% Depletion Schedule)

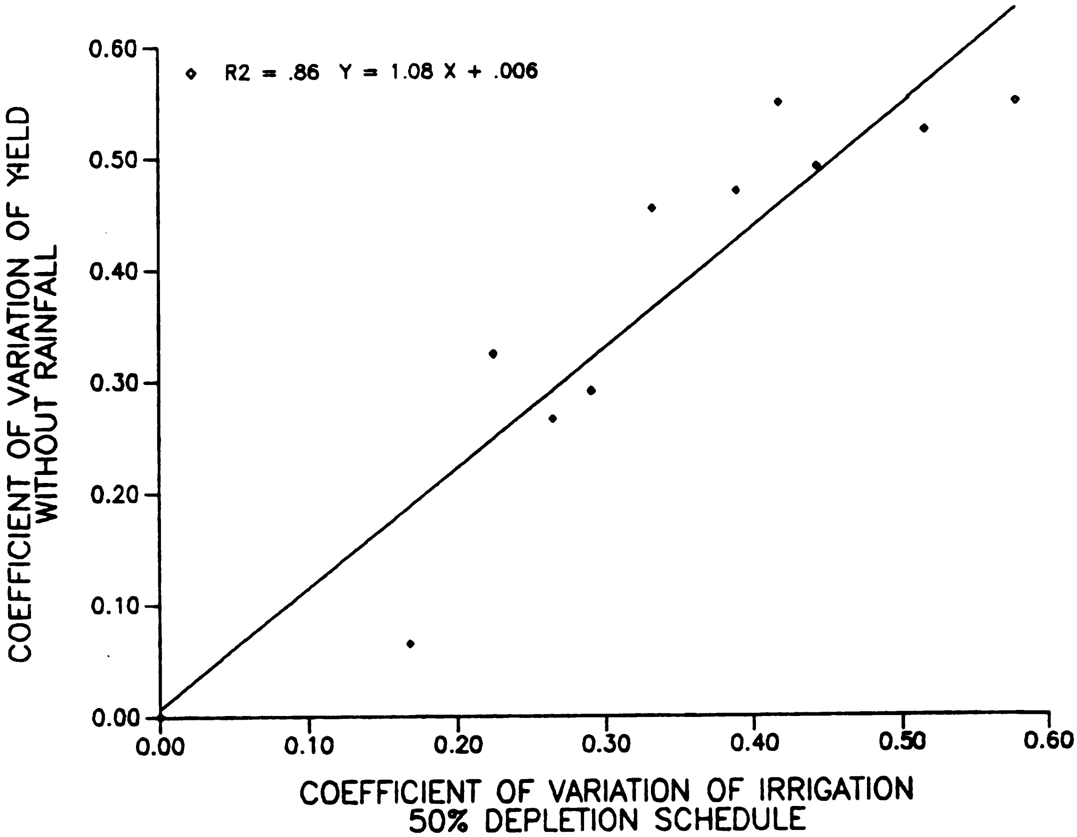

Figure 20. CV of Irrigation and CV of Yield Without Rainfall (50% Depletion Schedule)

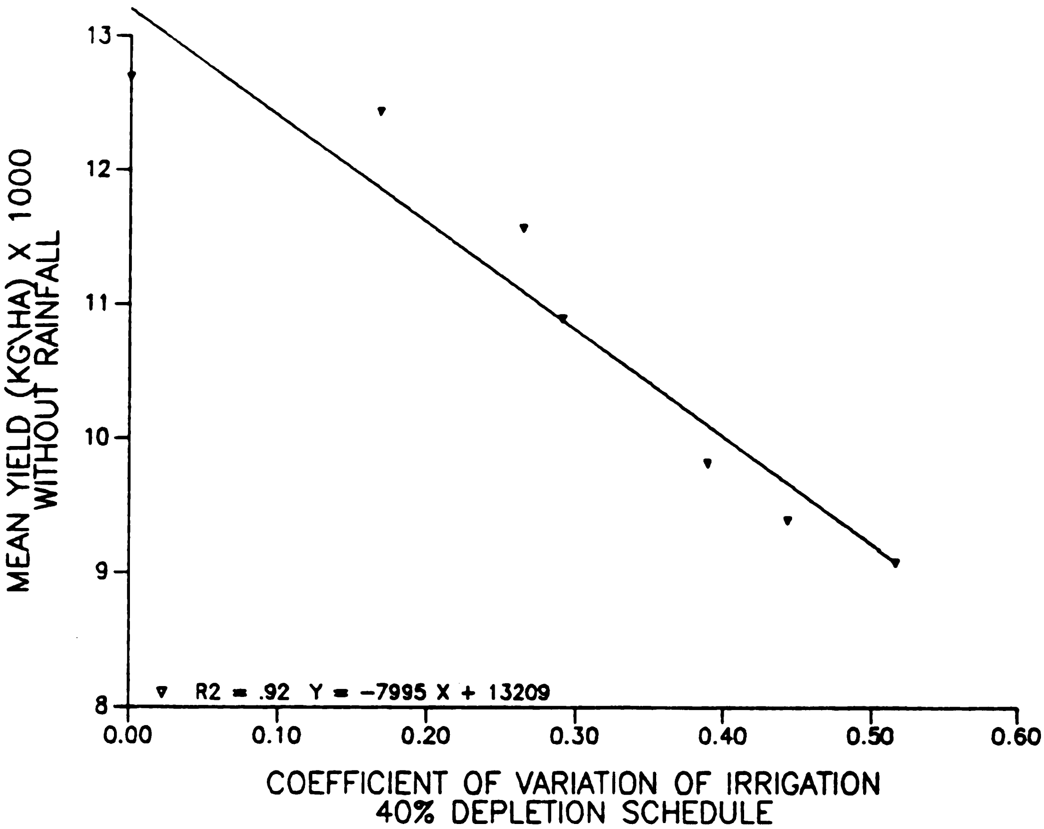

Figure 21. CV of Irrigation and Mean Yield Without Rainfall (40% Depletion Schedule)

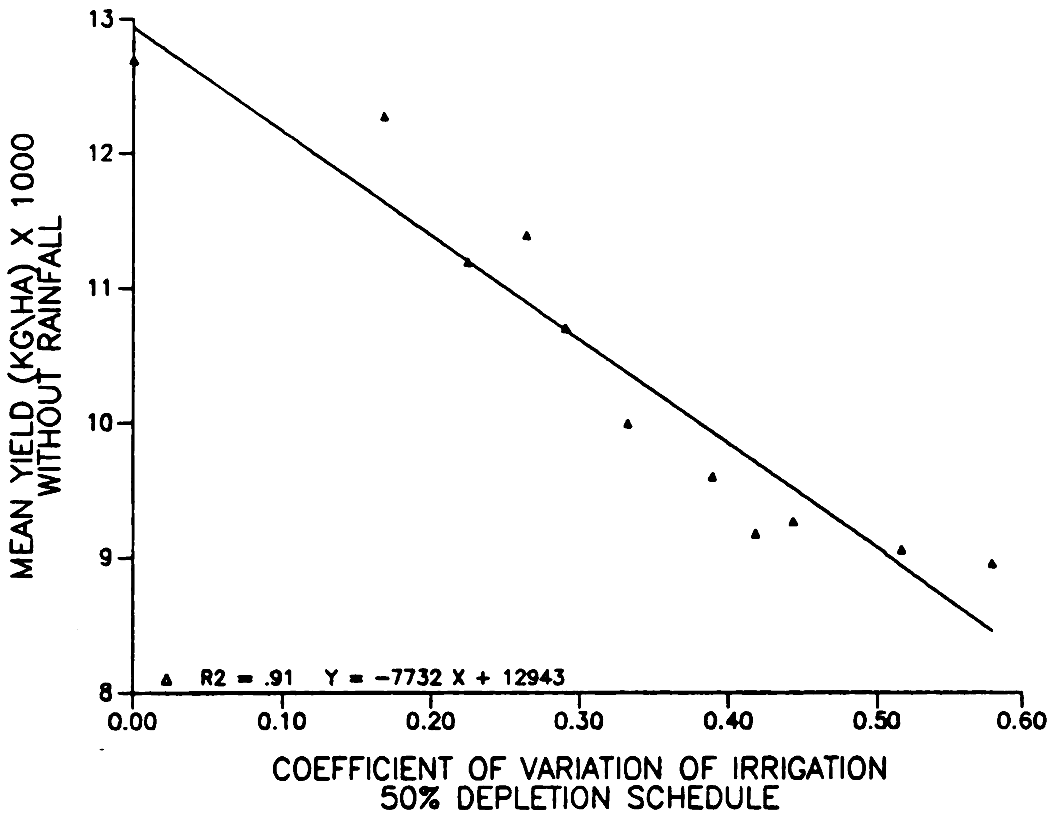

Figure 22. CV of Irrigation and Mean Yield Without Rainfall (50% Depletion Schedule)

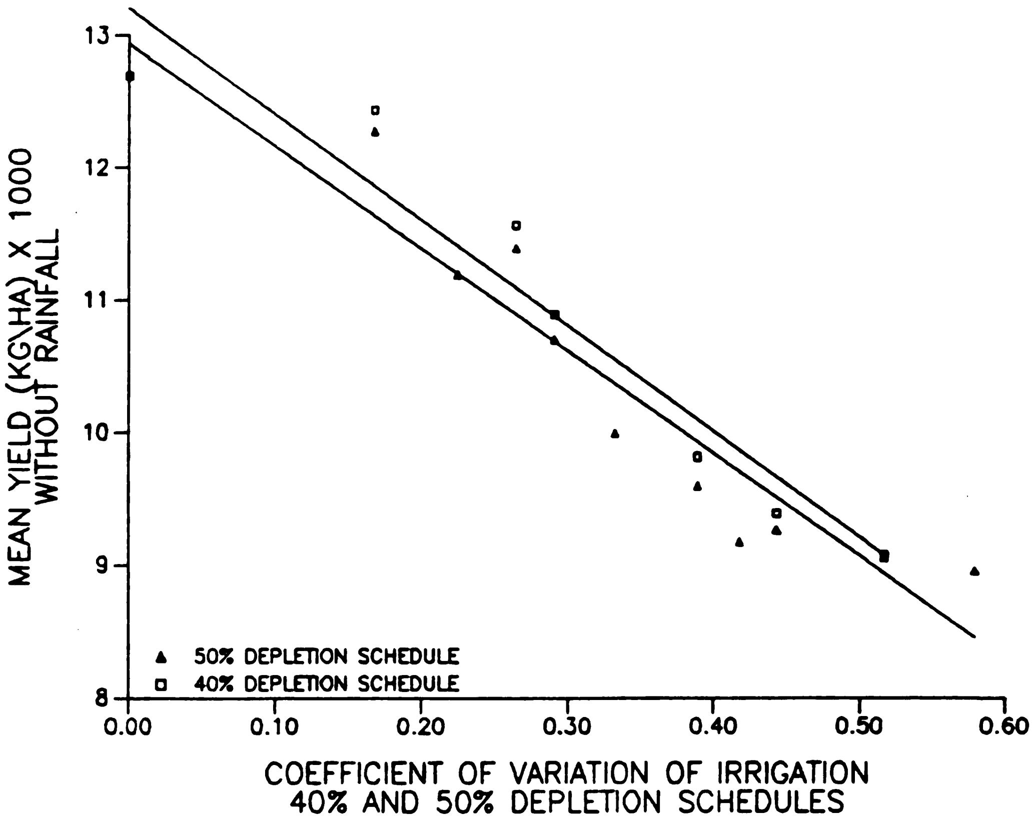

Figure 23. CV of Irrigation and Mean Yield Without Rainfall: 40% and 50% Depletion Scheduling Comparison

Figure 20 shows the relationship between CV of irrigation and CV of yield without rainfall. As can be seen from the regression line and equation ($y = 1.08x + .006$), the relationship between CV of irrigation and CV of yield is very close to 1 : 1. Essentially, in a situation where all of the crop water requirement is supplied by rainfall, CV of the irrigation system will approximately equal the CV of the maize yield.

From Figure 22, one can see that in a situation where no rainfall occurs, or when CV of irrigation is adjusted to account for all rainfall, there is a decrease in yield of about 750 kg/ha or about 6% for every 10% decrease in irrigation uniformity.

In this case, irrigation scheduling strategy is more critical than in a situation where rainfall occurs. But scheduling still does not have a significant effect on CV of yield or mean yield.

B. Verification of Adjusted Coefficient of Variation

The uniformity of center pivot irrigation is commonly measured using containers spaced at equal intervals along the pivot radius. The pivot is allowed to pass over the cans and the resulting depths of water are measured. This procedure, however, only measures an initial uniformity of irrigation water applied without consideriing the effect of additional uniform water application through rainfall. The theoretical been presented in the Methods section. The purpose of this analysis is to determine whether or not this proposed adjustment is valid.

Assuming an initial soil water content of 85% (75.1 mm), adding the effective rainfall from 1984, and subtracting the water remaining in the soil profile at harvest, a total rainfall volume of 158.8 mm was calculated. This rainfall was assumed to be uniform over the entire field area. Under the 50% depletion scheduling strategy, 247.0 mm of water was applied by irrigation. Thus, irrigation supplied 60 % of the total crop water requirement. Using the equation for adjusted CV presented in the Methods section, the CV of each irrigation system has been altered to reflect the addition of this rainfall. Original CVs and adjusted CVs are presented below in Table 7 .

Table 7 . Adjusted CV for 1984 Rainfall

ORIGINAL CV	ADJUSTED CV
0.00	0.00
.17	.10
.22	.13
.26	.16
.29	.17
.33	.20
.39	.23
.42	.25
.44	.26
.52	.31
.58	.35

The relationship between mean yield with rainfall (based on measured CV), mean yield without rainfall and mean yield based on adjusted CV is presented in Figure 25. In theory, the CV adjusted vs mean yield line should lie exactly over the CV without rainfall line . As can be seen in Figure 24, there was movement toward the CV without rainfall line, however the shift is not complete.

This is most likely due to the fact that the adjusted CV only reflects the CV of water application weighted by volume. But CV of water application under humid conditions is not a static parameter over time. With additions of 100% uniform rainfall occurring periodically throughout the growing season, CV changes. This is reflected in Table 8. and Figure 25 for a system with a measured CV of .52 (adjusted CV =.31) under 1984 rainfall conditions.

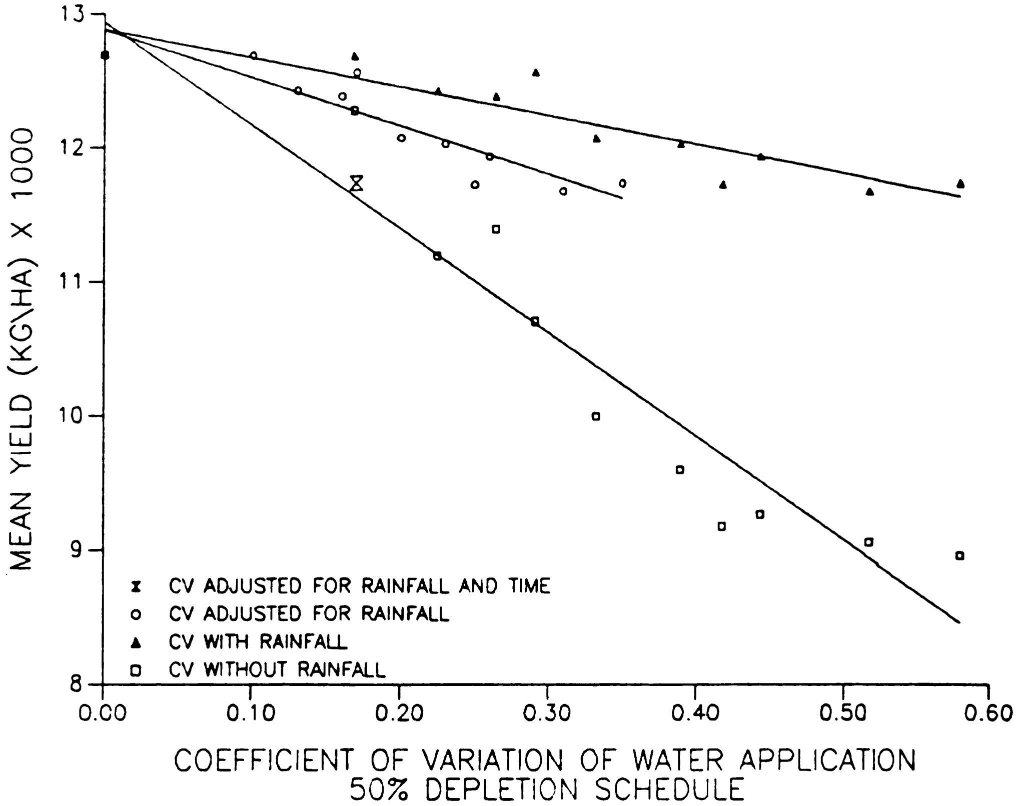

Figure 25. Graphical Validation of Adjusted CV

Table 8. Water Application CV Changes Over Time (1984)

DATE	RAIN (TO DATE) MM	IRRIGATION (TO DATE) MM	CV
5/10-6/13	54.10	0	0
6/14-6/19	54.36	19	.14
6/20-6/23	55.12	38	.21
6/24-6/28	56.13	57	.26
6/29-7/03	56.13	76	.29
7/04-7/18	112.52	95	.24
7/18-7/28	134.37	114	.24
7/29-8/01	134.37	133	.26
8/02-8/07	134.37	152	.28
8/08-8/11	134.37	171	.29
8/12-8/16	134.37	190	.29
8/17-8/21	134.37	209	.32
8/22-8/26	134.37	228	.31
8/27-9/10	158.75	247	.30

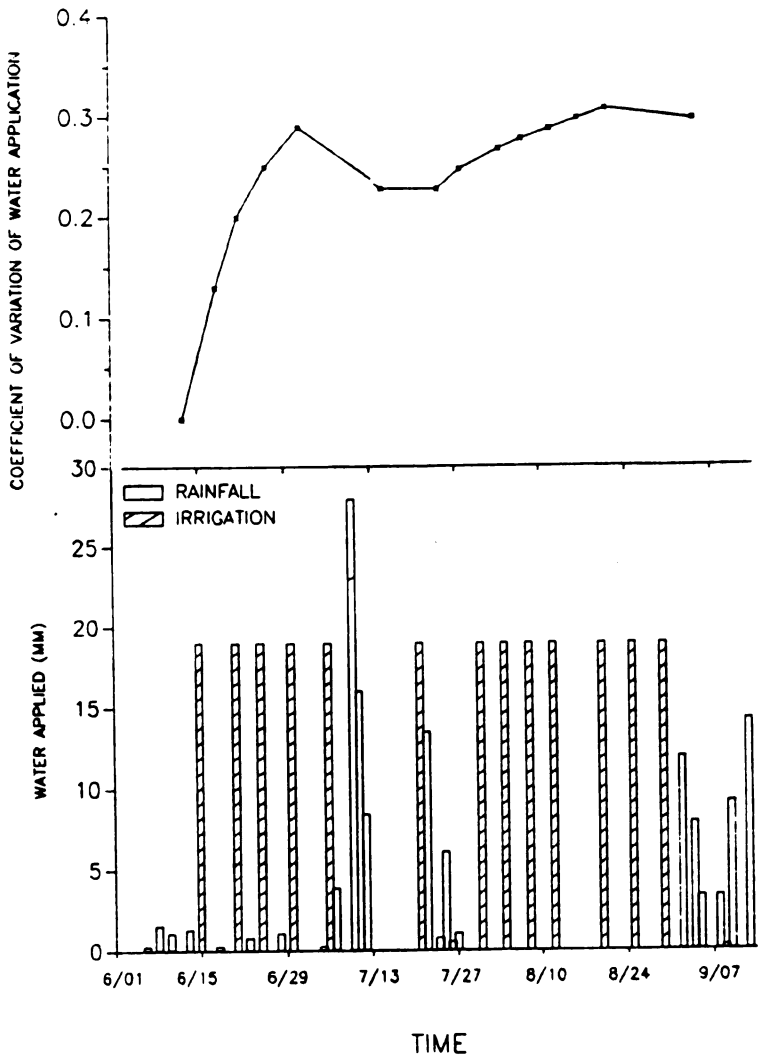

Figure 26. Coefficient of Variation of Water Application Changes Over Time

Table 8 and Figure 26 give some insight into why the adjusted CV tends to give a conservative estimate of mean yield. Although the adjusted CV of .31 reflects the uniformity of water application over the entire season, in fact, the CV is at .31 for less than one quarter of the total growing season. If each uniformity in Table 8 is weighted by the number of days over which it occured and a seasonal mean CV is calculated, then the coefficient of variation for the system is adjusted downward again to .16 . When this point is plotted in Figure 25, the adjustment is a more accurate estimate of expected yield. It should also be noted that crop sensitivity to non-uniform water application changes over the course of the season.

The relationship between measured CV and adjusted CV based on percentage of crop water requirement supplied by rainfall is shown below in Figure 27 . This relationship was developed using the equations proposed in the Methods section. By finding CV measured on the horizontal axis and drawing a line upward to the line which indicates percentage of effective rainfall (i.e. rain which does not runoff or deep percolate) and then over to the vertical axis, adjusted CV may be estimated. Table 9 from Bartholic et.al. presented below, estimates potential yearly irrigation requirements for all regions in Michigan. Employing an irrigation requirement value

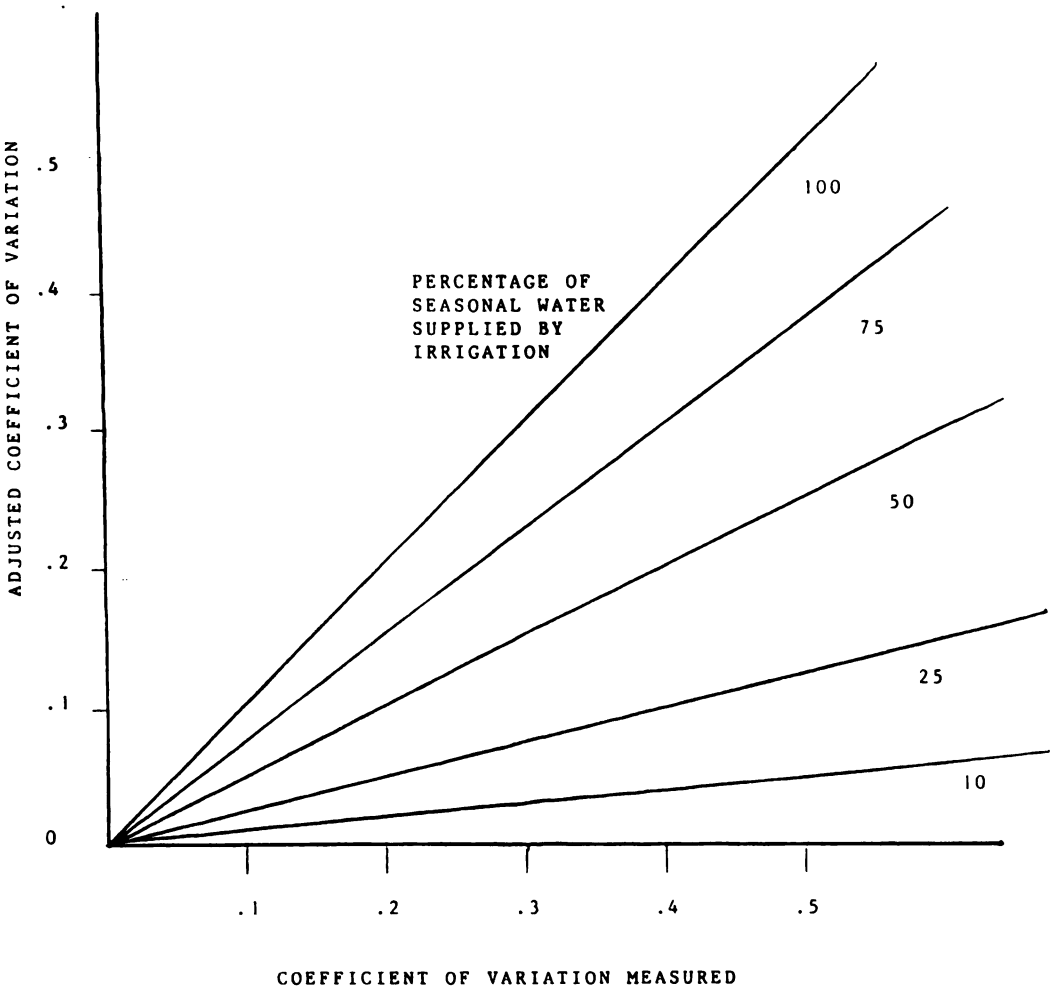

Figure 27. Nomograph for Estimating Adjusted CV

from Table 9 and estimating total crop water requirement, one may then determine the percentage of effective rainfall and the adjusted CV.

Table 9. Potential Seasonal Irrigation Requirements for Corn in Nine Michigan Districts

District	Potential Irrigation Requirement (mm)*		
	Corn	Soybeans	Dry Beans
Upper Penninsula	47.2	33.8	22.3
Northwest	137.9	110.2	95.3
Northeast	104.4	81.0	66.5
West Central	176.5	138.4	114.3
Central	188.0	161.0	135.6
East Central	190.0	162.3	133.9
Southwest	229.7	201.4	141.5
South Central	215.6	184.9	133.6
Southeast	236.7	206.8	149.9

* Irrigation requirment based on an estimated efficiency of 85%.

As noted above, the adjustment to the CV proposed here does give a conservative estimate of yield effect. The adjusted CV, however, is a more accurate expression of the effect of irrigation non-uniformity on yield in humid regions than is the traditionally measured CV. In addition, the adjusted CV may be determined prior to the growing season based on historical weather data. The most important advantage to CV adjustment for rainfall is in the standardization of uniformity recommendations. Presently, the recommended uniformity level for center pivot irrigation is .15 or less. (SCS). This recommendation is based on the assumption that most if not all of the crop water requirement is supplied by irrigation. In regions where much of the crop water is supplied by rainfall, a much lower level of irrigation uniformity may be supported.

2. Application Efficiency Considerations

The application efficiency of an irrigation system is defined as the percentage of water applied that is actually stored in the rootzone compared to the total water applied (Hanson et. al. 1979). When the rootzone is not fully irrigated the application efficiency has been defined by Wu and Gitlin (1981) as

$$E_a = 100 \left(\frac{V_r (1 - P_D)}{V_a} \right)$$

where E_a is the application efficiency, V_r is the volume of water required to fill the rootzone, P_D is the percent of deficit, and V_a is the volume of water applied.

The relationship between the coefficient of variation, irrigation deficit and application efficiency is based on probability and normal distribution function. In the case where irrigation volume applied is equal to the irrigation volume required, the irrigation deficit is equal to approximately .4 times the coefficient of variation for the center pivot system (Bralts,1986,) . In this instance, the application efficiency can be determined by the equation

$$E_a = 100 \left(\frac{V_r \,(1 - P_D)}{V_a}\right) = 100\,(1 - 0.4\ CV)$$

A dimensionless plot of the cumulative frequency curve is given in Figure 28 which shows the required irrigation depth in the rootzone for a CV of .4 and an application efficiency of approximateley 84%.

When rainfall is considered in determining application efficiency over an entire season, both the degree of deficit and excess are reduced. Using Figure 28 as an example, if the seasonal crop water requirement is 250 mm (10 in.) and if 50 % of this requirement is met by rainfall, then the area of the field receiving 0 mm from irrigation will have received 125 mm from rainfall which reduces the deficit by half. Conversely, the area which would have received 500 mm from irrigation will receive 250 mm from irrigation and 125 mm from rainfall decreasing the maximum excess application from 500 mm to 375 mm. Figure 29 presents the original system CV shown in Figure 28 compared to the application efficiency after rainfall is considered.

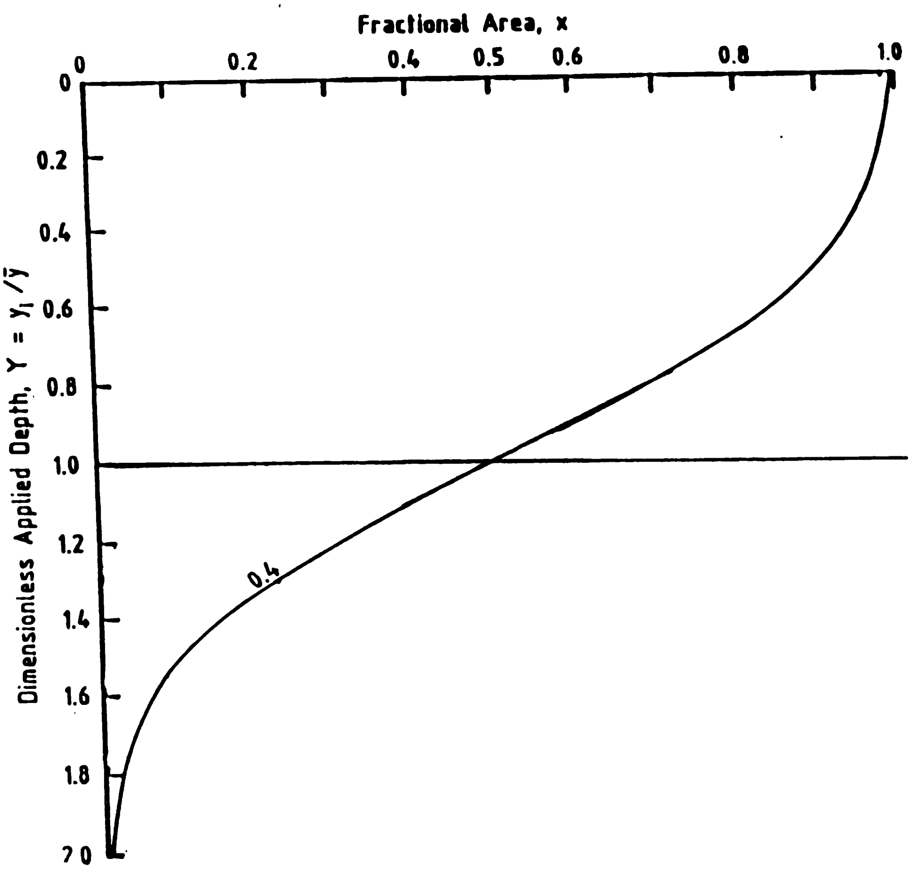

Figure 28. Cumulative Frequency Distribution for a CV of .4 (Not Adjusted for Rainfall)

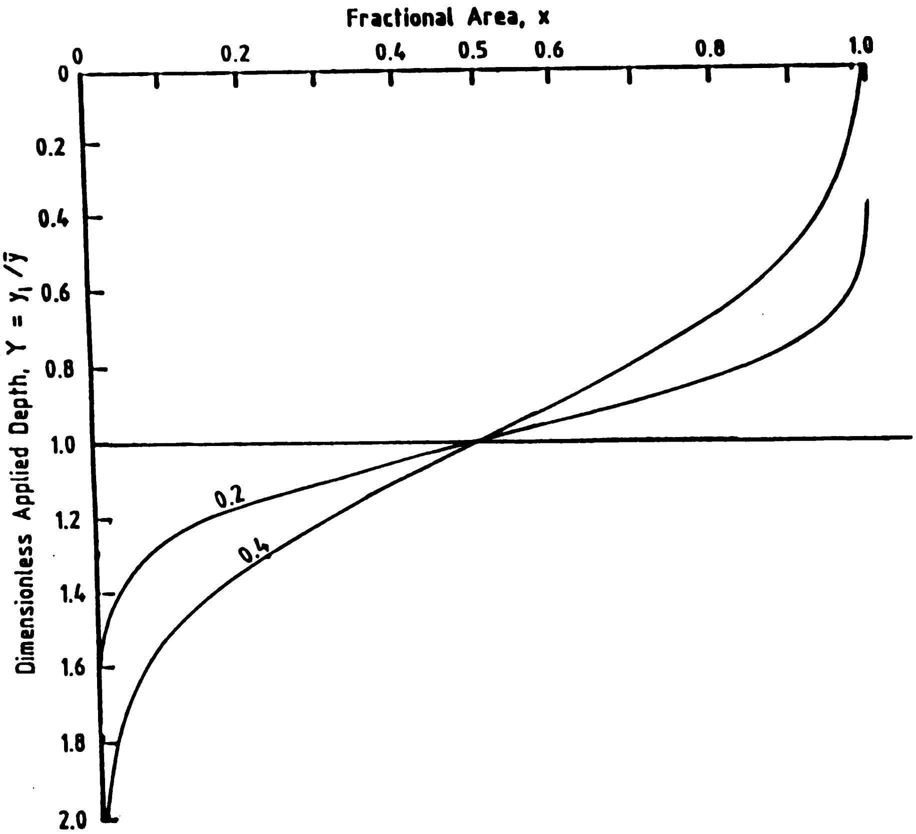

Figure 29. Application Efficiency Comparison Between Original and Adjusted CVs

C. Irrigation Uniformity Effects on Economics and Management

1. Irrigation Scheduling

Figures 29 and 30 present the income loss per 40.5 ha (100 ac) associated with different irrigation scheduling strategies under humid and dry conditions. The 30 year average cost per 19.0 mm irrigation per 40.5 ha for Michigan, Spinks sandy loam soil has been determined by Algozin (1986) to be $392.00 . Table 10 below shows the cost per season of total irrigation for the three different strategies under humid conditions compared with the average benefit for increased yield (based on $2.00/bushel profit for each additional bushel of maize produced).

Table 10. Irrigation Scheduling Costs (With Rainfall)

	TREATMENT		
	40%	50%	60%
NO. OF 19 MM APPLICATIONS REQUIRED	14	13	12
TOTAL COST OF IRRIGATION /40.5 HA (1984)	$5488	$5096	$4704
BENEFIT/COST	.68	.71	-

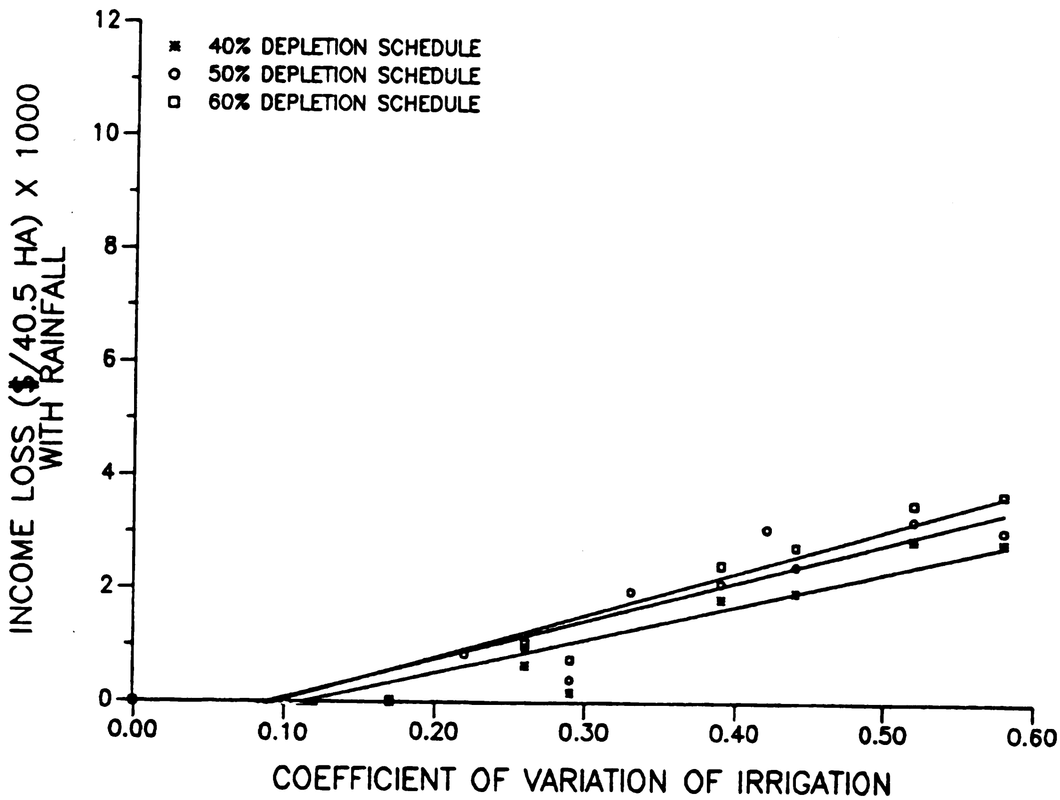

Figure 30. Income Loss Under Different Irrigation Schedules (With Rainfall)

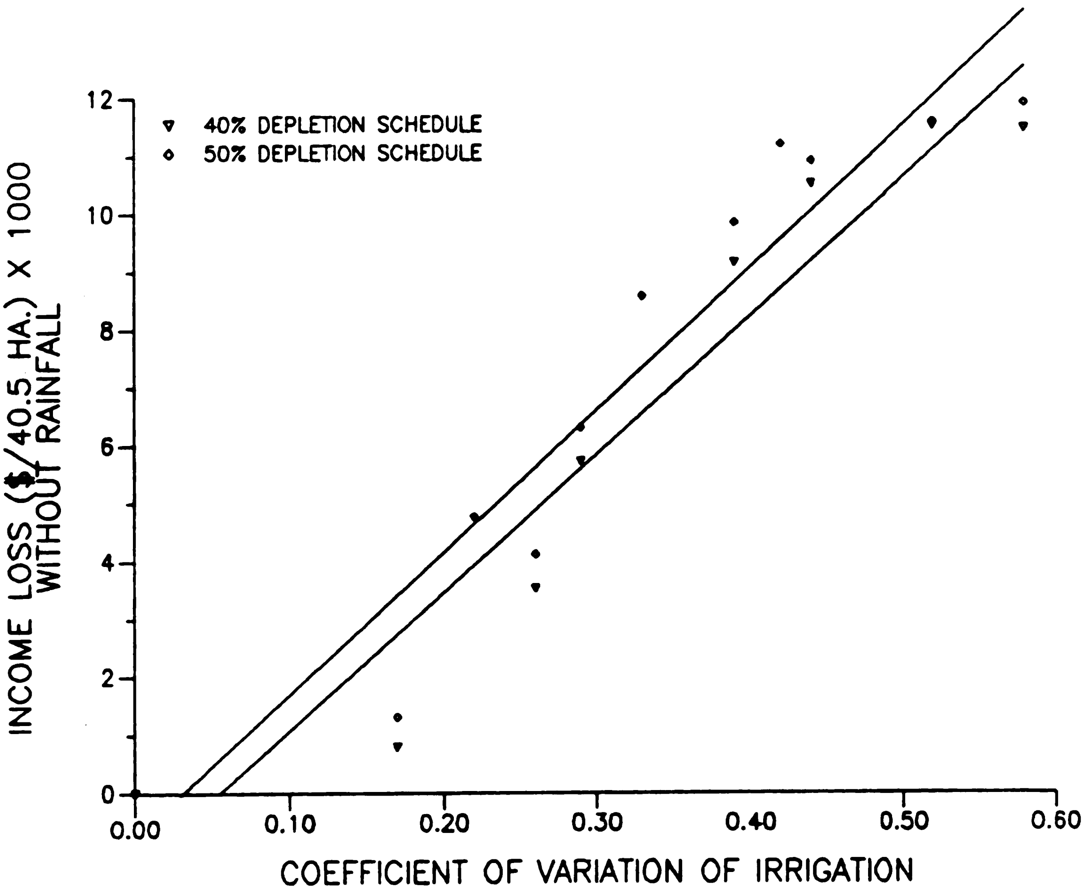

Figure 31. Income Loss Under Different Irrigation Schedules (Without Rainfall)

Table 11 below presents costs and benefits of different irrigation scheduling strategies under conditions without rainfall.

Table 11. Irrigation Scheduling Costs (Without Rainfall)

	TREATMENT	
	40%	50%
NO. OF 19 MM APPLICATIONS REQUIRED	24	23
TOTAL COST OF IRRIGATION /40.5 HA (1984)	$9408	$9016
BENEFIT/COST	1.43	---

From Table 10 and Figure 29 , it can be seen that the average benefit cost ratio for the more conservative scheduling regimes is less than one. This indicates that under rainfall conditions, scheduling irrigation at higher levels of soil moisture depletion is a more economically sound strategy except at very high levels of non-uniformity.

Figure 30 and Table 11 indicate that under conditions where no rainfall occurs, there is some benefit to scheduling irrigation at a higher moisture content. It should be noted, however, that the cost per irrigation estimate used in this analysis is the same as that used for the analysis with rainfall ($392.00/40.5 ha). In reality, an irrigated area where no rainfall occurs would be likely to have a much lower water table and substantially higher pumping costs than those found in Michigan.

2. Effect of Rainfall on Economics of Irrigation Uniformity

Figure 31 shows income loss per 40.5 ha (100 ac) in humid and dry irrigation situations. As can be seen from this figure, income loss under the rainfall conditions analyzed here (1984) are insignificant except at very low levels of uniformity. Conversely, under the scenario where no rainfall has occurred, income loss is significant even at moderate levels of non-uniformity.

This situation may have some important effects on farm management decision making. In terms of technology selection, farmers in humid regions are able to select irrigation technologies which are less uniform and less expensive, such as big gun rather than center pivot systems. A survey carried out among St. Joseph County irrigators by the author in 1986 indicates that this is true. The survey showed that more than half of the irrigation in the county was done with less expensive big gun irrigation than with center pivot.

Improvement of existing technology is also greatly

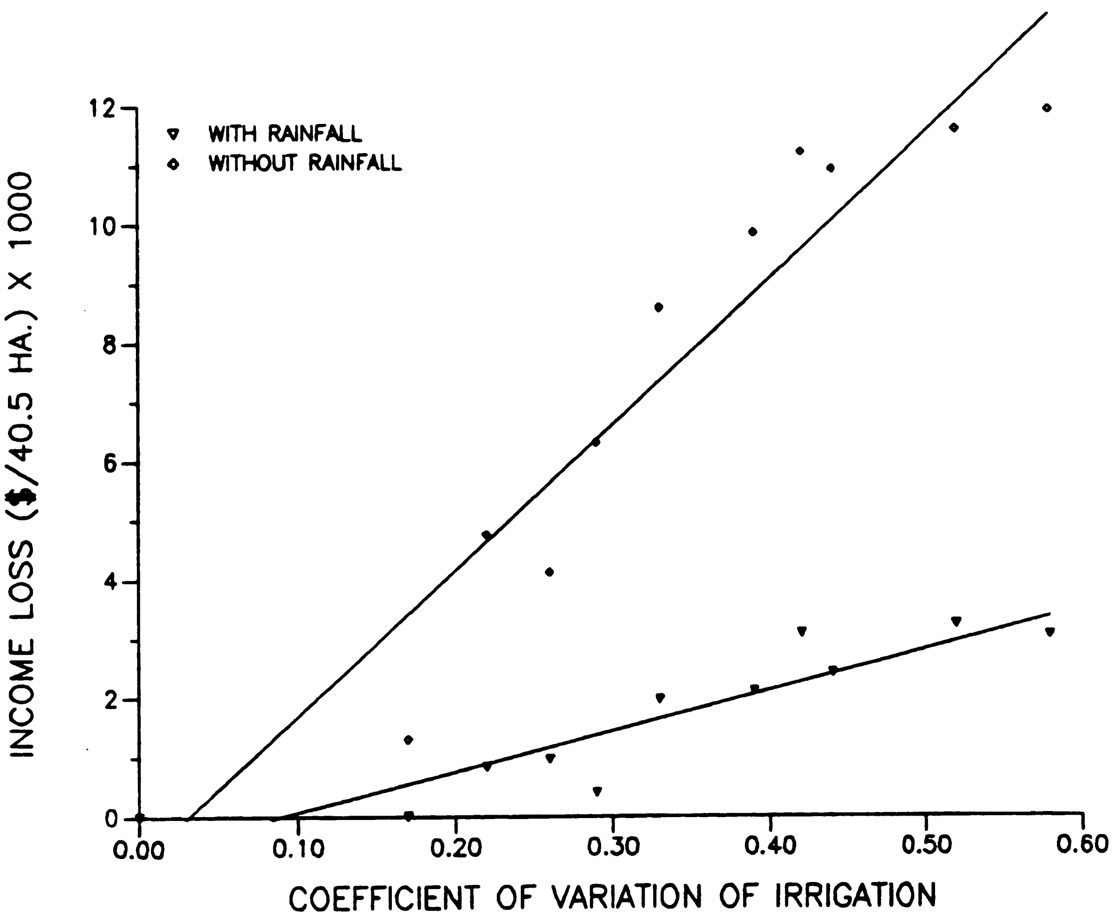

Figure 31. Income Losses Associated with Non-Uniform Irrigation: Humid vs Dry Conditions

influenced by the proportion of seasonal water supplied by precipitation. As noted previously, SCS in St. Joseph County has evaluated more than 90 irrigation systems over the past four years. Most of these systems have been found to have sub-standard uniformities, yet few if any of the irrigators have improved their irrigation systems. If the CVs of these systems are adjusted to reflect the addition of uniform rainfall to the irrigated area (approximately 45% of the crop water requirement for corn is supplied by rainfall) then a system CV as low as .30 has an adjusted CV of .16, a nearly acceptable value.

V. CONCLUSIONS AND RECOMMENDATIONS

The objectives of the proposed research have been addressed in full. The effect of irrigation uniformity on coefficient of variation of yield and mean yield has been evaluated for both humid and dry conditions through the use of a simulation model. In addition, the theoretical basis for and practical applications of an adjusted coefficient of variation considering rainfall have been presented. This adjusted CV has also been verified. Economic analysis with respect to the effects of non-uniformity and rainfall on scheduling and technology management has been carried out.

The specific conclusions of this research are:

1. The coefficient of variation of yield and mean yield are related to coefficient of variation for an irrigation system. In an environment where 100% of the crop water requirement is supplied by irrigation, or if CV of irrigation is adjusted to account for volume and weighted to account for timing of rainfall, then the expected CV of yield is approximately that of the irrigation system. In addition, yield decrease is approximately 6% for every 10% increase in coefficient of variation of irrigation.

2. Rainfall is an important mitigating factor in uniformity of water application in humid regions. An adjustment to the CV of an irrigation system reflecting the percentage of seasonal crop water supplied by precipitation allows for a more accurate estimate of non-uniformity effects on application efficiency and crop yield than the traditionally measured CV.

3. When the average seasonal uniformity is weighted to express the length of time over which each different uniformity level occurs, a very accurate estimate of yield reduction due to non-uniform irrigation can be made.

4. Irrigation scheduling at higher available water contents in humid regions (i.e. scheduling irrigation when only 40% of available water is depleted rather than waiting until 50% or 60% of the available soil water is depleted) is not economically sound except at very low levels of uniformity. The practice of scheduling in this manner may be feasible in arid regions provided that water and energy costs are low.

5. Because of the existence of relatively substantial rainfall inputs, irrigation non-uniformity is not as important an economic issue in humid areas as it is in arid regions. This applies particularly with regard to irrigation technology selection and irrigation system repair

Recommendations for further research include:

1. Analysis of other environmental factors such as spatial variability of soil types, which may also affect irrigation uniformity.

2. Historical analysis of seasonal timing and volume of rainfall related to crop growth stages to further refine adjustments to CV.

3. Validation of adjustments to CV with other soils and crops.

4. Analysis of yield loss due to nitrate leaching at higher application levels in non-uniform irrigation as well as post season nitrate loss in areas where irrigation deficits have occured.

APPENDIX A

SCS Center Pivot Evaluation Procedure

SCS Center Pivot Evaluation Procedure

Uniformity estimates used in this work are based on actual system evaluations performed by the St. Joseph County Soil Conservation District on center pivot irrigation systems in the St. Joseph area. These evaluations have been performed during the summers from 1983 through 1985. The following is an overview of the SCS uniformity evaluation procedure for center pivot irrigation systems.

Evaluations of irrigation systems are performed to determine adequacy of irrigation water management. The major factors which must be considered in making this determination are uniformity, total depth of application and maximum application rate. Irrigation water application should be as uniform as possible for maximum efficiency. The total depth of water applied should be sufficient to meet crop needs but should not exceed the water holding capacity of the soil to the bottom of the rootzone. The maximum application rate should not exceed the infiltration rate of the soil so that runoff and erosion do not occur.

A center pivot irrigation system operates by moving a lateral sprinkler line in a circle around a stationary central pivot point. The lateral is supported by self propelling towers mounted on wheels. The speed at which the system moves is controlled by the speed of the end (farthest from the pivot) tower. Generally, the lateral irrigates a circular area. See Figure 1 for a schematic drawing of center pivot sprinkler operation. The attachment of a big gun or cornering attachment allows the irrigation of a square area. The big gun or cornering attachment only operates part of the time and consequently large changes in the uniformity of a system may be observed when the gun is off versus when it is on.

The SCS recommended procedure for estimating irrigation uniformity for a center pivot system is first to set cans in a line along the radius of the lateral. Normally, quart oil cans with the tops removed are used for catching precipitation. Cans may be set on (or slightly imbedded in) the ground if the crop is small enough to permit unobstructed catches. If not, cans should be attached to stakes which hold them above the vegetation. The catch cans should be placed at a uniform interval, usually 30 feet, beginning this distance from the pivot and extending to a point beyond the wetted area.

After the system has passed the can line, the depth of water in each can is measured and recorded. In a center pivot evaluation each can, providing that the distance between the cans is constant, represents a different area. Therefore, in calculating the uniformity of the system, a weighting factor for each can must be calculated. When cans are set at a uniform spacing the area weighted factor is equal to the can number. The first can is set 30 feet from the pivot and represents an area from 15 feet to 45 feet from the pivot. The second can is set 60 feet from the pivot and 30 feet from the first can. It represents an area from 45 feet to 75 feet from the pivot and so on. The area of a circle is equal to pi times the square of the radius or the distance to the furthest point from the pivot represented by that catch can. The area represented by can 1:

$$= 3.1416 * 45^2 - 3.1416 * 15^2$$

$$= 5654.88 \text{ sq. ft.}$$

The area represented by can 2:

$$= 3.1416 * 75^2 - 3.1416 * 45^2$$

$$= 11309.76 \text{ ft. sq.}$$

The area represented by can 3:

$$= 3.1416 * 105^2 - 3.1416 * 75^2$$

$$= 16964.54 \text{ sq. ft.}$$

The weighting factor for can 1 is the ratio of its area to itself or:

$$5654.88 / 5654.88 = 1$$

The weighting factor for can 2 is the ratio of its area to the area of can 1:

$$11309.76 / 5654.88 = 2$$

And the weighting factor for can 3 is the ratio of its area to can 1:

$$16964.54 / 5654.88 = 3$$

This procedure may be followed for determining the weighting factors of all cans along the radius.

APPENDIX B

CERES - Maize and SCHEDULER Information

I. CERES-Maize Model

1. Introduction

CERES-Maize is a daily incrementing simulation model of maize growth, development and yield. CERES-maize is available in two versions; the standard, which simulates the effects of genotype, soil properties and weather on growth and in a nitrogen version which models the growth and yield effects of soil and plant nitrogen on the crop. In order to accurately determine maize growth, development and yield, the model simulates such physical and biological processes as phenological development, growth of leaves and stems, biomass accumulation and partitioning, soil water balance and plant water use, and soil nitrogen transformations. The CERES-Maize model is appropriate for use on most IBM compatible microcomputers with at least 256K of memory and Microsoft DOS operating systems (version 2.0 or higher).

2. Input Files

The input requirements for the CERES-maize model are contained in four files. Most of the required parameters are readily available or may be easily estimated. This section will discuss each of the files and parameters.

a. Climate File

The climate file requires daily inputs of solar radiation, maximum and minimum temperature and precipitation. This information is used to estimate evapotranspiration and to track soil mosture status.

b. Soil Water File

The following inputs are required for the soil water file:

Soil Albedo or soil reflectivity. Values range from

sandy soils.

Stage 1 soil evaporation coefficient This coefficient varies from 6 mm in sands and heavy clays to 9 mm in loams and 12 mm in clay loams.

Whole profile drainage rate coefficient This coefficient is used to estimate drainage from the whole soil profile. The drainage coefficient is calculated for each layer and the minimum layer value is used as the coefficient for the whole profile.

Runoff curve number This number is derived from SCS runoff estimates for different hydrological soil groups.

Soil layer thickness Up to 10 soil layers may be identified as model inputs. To insure accurate water balance estimates, the minimum pedon depth should be 2.0 m, within 30 cm of the soil surface, no layer should be thicker than 15 cm, and below 30 cm of the soil surface no soil layer should be thicker than 30 cm.

Lower limit of plant extractable water Estimates are available for some representative soils or the value can be calulated from sand, silt clay and organic carbon contents of the soil, and bulk density.

Drained upper limit See above.

Saturation water content Once the drained upper limit is calculated, the saturation water content may be estimated based on that value and the soil porosity.

Root distribution weighting factor This factor is used to estimate the relative root growth in all soil layers where root growth actually occurs. In the case of physical or chemical constraints to growth, the weighing factor should be reduced accordingly.

c. Genetic File

The genetic inputs to the CERES-Maize model include growing degree days (from seedling emergence to end of juvenile phase and from silking to physiological maturity), photoperiod sensitivity, potential kernal number and potential kernal growth rate. At present, CERES-Maize documentation contains genetic input values for several commonly grown commercial corn varieties. For other cultivars, these genetic input values may be estimated or easily measured.

d. Irrigation File

The irrigation file contains inputs for date of irrigation and amount of application.

3. Model Operation

The biological processes modeled by CERES-Maize are soil water balance, phenological development and crop growth. Soil water balance is evaluated using inputs for rainfall and irrigation. The model determines distribution and movement of water through each layer in the soil profile. Soil water redistribution and drainage are then calculated establishing conditions from which potential and actual ET are determined.

The crop phenological development parameters are used by the model to determine the dates and duration of each growth stage of the crop. The occurance of these growing stages are dependant upon temperature, photoperiod, and genetic characteristics of the crop, all of which are required inputs to the model.

The growth of the crop (i.e. the accumulation and partitioning of biomass within the plant) is based upon water and temperature stresses primarily. The model calculates potential dry matter production and actual production.

4. Model Validation

The CERES-Maize model has been evaluated at a number of different locations under a variety of growing conditions. The results of these evaluations are discussed in Jones and Kiniry (1986). Generally, CERES-Maize has been found to be sensitive to input data particularly with regard to soil water information. Thus, the accuracy of CERES-Maize is highly dependant on the quality of input data. The model has performed accurately, especially in estimating maximum leaf area index, maximum above-ground biomass and grain yield.

Although CERES-Maize has been evaluated in many areas where rainfed agricultural production is common, there has been at present little validation in southern Michigan. The necessary inputs for the model, however, are available and preliminary investigations suggest that CERES-Maize is valid for this region as well.

II. SCHEDULER

The MSU microcomputer irrigation SCHEDULER program is an interactive program designed for use by Agricultural Extension Agents and Soil Conservation Districts. SCHEDULER may be operated using actual weather data obtained from a weather station, or may be used to schedule irrigation based on historical weather information.

At present, SCHEDULER supports three crops; corn, soybeans and potatoes. The primary use of SCHEDULER to date has been in irrigation scheduling for corn.

SCHEDULER operates by employing user prompted inputs for weather (maximum temperature, minimum temperature, windspeed, humidity, total and net solar radiation) rainfall and irrigation to calculate soil moisture status. Beginning with an assumed or measured soil moisture, SCHEDULER calculates ET based on the weather (actual or historical). This water is subtracted from the soil profile. Then using the inputs for rainfall and irrigation, SCHEDULER adds this water to the profile and generates a new soil moisture estimate.

Scheduler has been in operation in St. Joseph County since 1983. Although comprehensive validation of the SCHEDULER algorithms is not completed, initial results are favorable. It should be noted that SCHEDULER has performed particularly well during dry years.

APPENDIX C

Additional Information

TURBO-PASCAL PROGRAM FOR CV CALCULATION

```
PROGRAM uniformity (INPUT,OUTPUT);
VAR
  a,b,c,d,e,f,g,h,i,j,k,l   :REAL;
{This is a program to calculate the coefficient of
variation for a center pivot irrigation system.  The values
input are a can weighting factor and a water quantity for
each catch can.  The output includes a calculation of the
weighted mean application and the coefficient
of variation}
BEGIN
 c :=0.0; {sum of the weights}
 d :=0.0; {sum of the catch can values}
 g :=0.0; {sum of the weighted values}
 h :=0.0; {sum of the weighted values squared}
REPEAT
 WRITELN ('Enter multiplier factor ');
 READLN (a);
 IF a <>0 THEN BEGIN

 WRITELN ('Enter amount of water in catch can ');
 READLN (b);
 c := c+a; {this adds up the values of the weights}
 d := d+b;  {this adds up the values of the catch cans}
 e := a*b; {this calculates the weighted value for each can}
 f := SQR(b)*a;{this squares the weighted value}
 g := g+e; {this sums the weighted values}
 h := h+f; {this sums the weighted values squared}

END  (* END IF *)
UNTIL  a = 0;
i := g/c; {this calculates the weighted mean}
j :=(h/(c-1.0)) - SQR(g)/(c*(c-1.0));
k :=SQRT(j)/i;
l := 100 * (1.0 - (0.798 * k));
  WRITELN ('The weighted mean value is ', i : 4:2);
  WRITELN ('The the variance for this system is ', j : 2:3);
  WRITELN ('The coefficient of variation for
            this system is ', k : 1:4);
  WRITELN ('Christiansens uniformity coefficient is  ', l:2:1);

END.
```

40% DEPLETION SCHEDULE

SYSTEM CV .1681

FACTOR	ACTUAL CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	65.71	48.90	12692	12692
2	61.29	45.61	12692	12692
3	40.31	30.00	12692	12692
4	34.80	25.90	12692	12692
5	34.80	25.90	12692	12692
6	34.80	25.90	12692	12692
7	33.10	24.63	12692	12692
8	32.03	23.84	12692	12692
9	25.90	19.27	12692	12692
10	29.82	22.19	12692	12692
11	27.10	20.17	12692	12692
12	28.16	20.98	12692	12692
13	25.90	19.27	12692	12692
14	25.40	18.90	12692	12692
15	25.40	18.90	12692	12692
16	24.30	18.08	12692	12683
17	25.90	19.27	12692	12692
18	25.90	19.27	12692	12692
19	25.90	19.27	12692	12692
20	23.74	17.68	12692	12568
21	24.85	18.49	12692	12690

22	24.85	18.49	12692	12690
23	24.80	18.46	12692	12690
24	22.09	16.44	12690	11455
25	22.64	16.85	12691	12141
26	23.74	17.67	12692	12565
27	22.64	16.85	12691	12141
28	21.53	16.02	12689	10816
29	24.85	18.49	12692	12690
30	25.40	18.90	12692	12692

ACTUAL CATCH		ADJUSTED CATCH	
MEAN	= 25.53	MEAN	= 19.00
ST.DEV	= 4.29	ST.DEV	= 3.19
CV	= .1681	CV	= .1681
CU	= 86.6%	CU	= 86.6%

YIELD WITH RAINFALL		YIELD WITHOUT RAINFALL	
MEAN	= 12691	MEAN	= 12440
CV	= .0001	CV	= .0413

40% DEPLETION SCHEDULE

SYSTEM CV .2643

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	35.40	29.56	12692	12692
2	42.50	35.49	12692	12692
3	50.20	41.92	12692	12692
4	28.10	23.47	12692	12692
5	16.80	14.03	12673	7369
6	17.20	14.36	12676	8029
7	21.30	17.79	12692	12596
8	21.30	17.79	12692	12596
9	21.30	17.79	12692	12596
10	23.50	19.63	12692	12692
11	22.20	18.54	12692	12690
12	18.60	15.53	12686	9839
13	19.50	16.29	12689	11389
14	19.50	16.29	12689	11389
15	19.50	16.29	12689	11389
16	19.50	16.29	12689	11389
17	20.40	17.04	12692	12404
18	20.40	17.04	12692	12404
19	21.30	17.79	12692	12596
20	22.20	18.54	12692	12690

21	24.50	20.46	12692	12692
22	25.20	21.05	12692	12692
23	20.30	21.96	12692	12692
24	21.30	17.79	12692	12596
25	22.20	18.54	12692	12690
26	30.20	25.22	12692	12692
27	9.10	7.60	8646	85
28	21.90	18.29	12692	12692
29	35.80	29.90	12692	12692
30	22.60	18.87	12692	12692

GENERATED CATCH		ADJUSTED CATCH	
MEAN	= 22.75	MEAN	= 19.00
ST.DEV	= 6.01	ST.DEV	= 5.02
CV	= .2643	CV	= .2643
CU	= 78.9%	CU	= 78.9%

YIELD WITH RAINFALL		YIELD WITHOUT RAINFALL	
MEAN	= 12486	MEAN	= 11570
CV	= .0760	CV	= .2593

40% DEPLETION SCHEDULE

SYSTEM CV .2908

FACTOR	ACTUAL CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	22.35	16.28	12689	11387
2	53.08	38.67	12692	12692
3	23.62	17.21	12692	12448
4	20.07	14.62	12678	8497
5	18.80	13.70	12671	6922
6	20.32	14.80	12680	8657
7	22.35	16.28	12689	11387
8	19.56	14.25	12675	7778
9	20.07	14.62	12678	8947
10	19.81	14.43	12676	8147
11	22.35	16.28	12689	11387
12	24.13	17.58	12692	12543
13	21.08	15.36	12684	9739
14	45.72	33.31	12692	12692
15	19.05	13.88	12672	7144
16	18.29	13.32	12688	6305
17	27.43	19.98	12692	12692
18	23.37	17.03	12692	12402
19	20.57	14.99	12682	8842
20	25.91	18.88	12692	12692

21	28.70	20.91	12692	12692
22	27.69	20.17	12692	12692
23	26.92	19.61	12692	12692
24	26.42	19.25	12692	12692
25	24.64	17.95	12692	12676
26	27.18	19.80	12692	12692
27	28.19	20.54	12692	12692
28	27.69	20.17	12692	12692
29	45.72	33.31	12692	12692
30	15.49	11.28	11867	2265

ACTUAL CATCH		ADJUSTED CATCH	
MEAN	= 26.08	MEAN	= 19.00
ST.DEV	= 7.58	ST.DEV	= 5.53
CV	= .2908	CV	= .2908
CU	= 76.8%	CU	= 76.8%

YIELD WITH RAINFALL		YIELD WITHOUT RAINFALL	
MEAN	= 12635	MEAN	= 10896
CV	= .0160	CV	= .2761

40% DEPLETION SCHEDULE

SYSTEM CV .3891

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	36.90	29.91	12692	12692
2	63.20	51.23	12692	12692
3	56.80	46.04	12692	12692
4	42.60	34.53	12692	12692
5	38.30	31.04	12692	12692
6	35.20	28.53	12692	12692
7	25.40	20.59	12692	12692
8	28.60	23.18	12692	12692
9	29.30	23.75	12692	12692
10	9.20	7.46	8414	78
11	11.60	9.40	9661	585
12	12.70	10.29	10528	1365
13	21.50	17.43	12692	12505
14	21.50	17.43	12692	12505
15	21.50	17.43	12692	12505
16	18.40	14.91	12681	8759
17	19.60	15.89	12688	10303
18	20.20	16.37	12690	11419
19	20.20	16.37	12690	11419
20	26.30	21.32	12692	12692

21	24.50	19.86	12692	12692
22	24.50	19.86	12692	12692
23	23.80	19.29	12692	12692
24	19.40	15.72	12687	10196
25	12.30	9.97	10283	1071
26	9.70	7.86	8663	97
27	18.50	15.00	12682	8850
28	30.40	24.64	12692	12692
29	40.20	32.58	12692	12692
30	33.50	27.15	12692	12692

GENERATED CATCH

MEAN = 23.44
ST.DEV = 9.12
CV = .3891
CU = 68.9%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 7.39
CV = .3891
CU = 68.9%

YIELD WITH RAINFALL

MEAN = 12116
CV = .1052

YIELD WITHOUT RAINFALL

MEAN = 9820
CV = .4574

40% DEPLETION SCHEDULE

SYSTEM CV .4430

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	33.10	28.72	12692	12692
2	48.20	41.82	12692	12692
3	52.50	45.55	12692	12692
4	8.40	7.29	8324	69
5	6.30	5.47	5563	0
6	28.60	24.81	12692	12692
7	13.20	11.45	12077	2470
8	16.80	14.57	12678	8251
9	16.80	14.57	12678	8251
10	15.90	13.79	12671	7025
11	0.00	0.00	2859	0
12	24.90	21.60	12692	12692
13	23.20	20.13	12692	12692
14	26.70	23.16	12692	12692
15	18.80	16.31	12690	11168
16	13.60	11.80	12453	2868
17	19.50	16.92	12692	12373
18	19.50	16.92	12692	12373
19	20.10	17.44	12692	12508
20	20.10	17.44	12692	12508

21	13.80	11.97	12543	3223
22	14.60	12.66	12607	4277
23	25.30	21.95	12692	12692
24	26.20	22.73	12692	12692
25	15.40	13.36	12668	6350
26	23.40	20.30	12692	12692
27	8.70	7.55	8651	82
28	42.60	36.96	12692	12692
30	35.20	30.54	12692	12692

GENERATED CATCH		ADJUSTED CATCH	
MEAN	= 21.90	MEAN	= 19.00
ST.DEV	= 9.70	ST.DEV	= 8.41
CV	= .4430	CV	= .4430
CU	= 64.4%	CU	= 64.4%

YIELD WITH RAINFALL		YIELD WITHOUT RAINFALL	
MEAN	= 12080	MEAN	= 9392
CV	= .1568	CV	= .4895

40% DEPLETION SCHEDULE

SYSTEM CV .5175

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	1.30	1.12	3109	0
2	9.20	7.96	8709	109
3	13.50	11.69	12297	2691
4	25.70	22.25	12692	12692
5	14.30	12.38	12580	3667
6	14.30	12.38	12580	3667
7	12.00	10.39	10569	1372
8	19.10	16.53	12690	11542
9	14.50	12.55	12597	4051
10	17.80	15.41	12685	9767
11	21.50	18.61	12692	12691
12	0.00	0.00	2859	0
13	14.80	12.81	12622	4448
14	18.00	15.58	12686	9868
15	19.10	16.53	12690	11542
16	27.70	23.98	12692	12692
17	22.40	19.39	12692	12692
18	14.20	12.29	12572	3578
19	14.90	12.90	12632	5621
20	22.40	19.39	12692	12692

21	23.40	20.26	12692	12692
22	28.20	24.41	12692	12692
23	6.30	5.45	5563	0
24	22.40	19.39	12692	12692
25	18.00	15.58	12686	9868
26	26.70	23.11	12692	12692
27	9.20	7.96	8709	109
28	36.10	31.25	12692	12692
29	26.50	22.94	12692	12692
30	53.20	46.05	12692	12692

GENERATED CATCH		ADJUSTED CATCH	
MEAN	= 21.95	MEAN	= 19.00
ST.DEV	= 11.36	ST.DEV	= 9.81
CV	= .5175	CV	= .5175
CU	= 58.7%	CU	= 58.7%

YIELD WITH RAINFALL		YIELD WITHOUT RAINFALL	
MEAN	= 11786	MEAN	= 9080
CV	= .1979	CV	= .5324

40% DEPLETION SCHEDULE

SYSTEM CV .5802

FACTOR	ACTUAL CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	1.27	1.01	3091	0
2	9.14	7.26	8307	68
3	13.46	10.69	10890	1686
4	25.65	20.37	12692	12692
5	14.48	11.50	12149	2526
6	14.48	11.50	12149	2526
7	11.94	9.48	9698	587
8	19.05	15.12	12683	9340
9	14.48	11.50	12149	2526
10	17.78	14.12	12674	7711
11	21.59	17.14	12692	12430
12	0.00	0.00	2859	0
13	14.73	11.69	12297	2691
14	18.03	14.31	12675	7832
15	19.05	15.12	12683	9340
16	23.37	18.55	12692	12690
17	19.05	15.12	12683	9340
18	27.69	21.98	12692	12692
19	22.35	17.74	12692	12583
20	14.22	11.29	11869	2332

21	4.83	3.83	4596	0
22	22.35	17.74	12692	12583
23	23.37	18.55	12692	12690
24	28.19	22.38	12692	12692
25	28.96	22.99	12692	12692
26	26.67	21.17	12692	12692
27	13.46	10.69	10890	1686
28	36.07	28.64	12692	12692
29	26.42	20.98	12692	12692
30	67.56	53.64	12692	12692

<u>ACTUAL CATCH</u>

MEAN = 23.93
ST.DEV = 13.89
CV = .5802
CU = 53.7%

<u>ADJUSTED CATCH</u>

MEAN = 19.00
ST.DEV = 11.03
CV = .5802
CU = 53.7%

<u>YIELD WITH RAINFALL</u>

MEAN = 11800
CV = .1959

<u>YIELD WITHOUT RAINFALL</u>

MEAN = 9097
CV = .5350

50% DEPLETION SCHEDULE

SYSTEM CV .1681

FACTOR	ACTUAL CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	65.71	48.90	12692	12692
2	61.29	45.61	12692	12692
3	40.31	30.00	12692	12692
4	34.80	25.90	12692	12692
5	34.80	25.90	12692	12692
6	34.80	25.90	12692	12692
7	33.10	24.63	12692	12692
8	32.03	23.84	12692	12692
9	25.90	19.27	12692	12690
10	29.82	22.19	12692	12692
11	27.10	20.17	12692	12692
12	28.16	20.98	12692	12692
13	25.90	19.27	12692	12690
14	25.40	18.90	12692	12690
15	25.40	18.90	12692	12690
16	24.30	18.08	12692	12673
17	25.90	19.27	12692	12690
18	25.90	19.27	12692	12690
19	25.90	19.27	12692	12690
20	23.74	17.68	12689	12468

21	24.85	18.49	12692	12687
22	24.85	18.49	12692	12687
23	24.80	18.46	12692	12686
24	22.09	16.44	12681	10659
25	22.64	16.85	12685	11363
26	23.74	17.67	12689	12646
27	22.64	16.85	12685	11363
28	21.53	16.02	12645	10143
29	24.85	18.49	12692	12687
30	25.40	18.90	12692	12690

ACTUAL CATCH

MEAN = 25.53
ST.DEV = 4.29
CV = .1681
CU = 86.6%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 3.19
CV = .1681
CU = 86.6%

YIELD WITH RAINFALL

MEAN = 12688
CV = .0009

YIELD WITHOUT RAINFALL

MEAN = 12278
CV = .0648

50% DEPLETION SCHEDULE

SYSTEM CV .2246

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	20.30	20.37	12692	12692
2	19.60	19.67	12692	12692
3	19.60	19.67	12692	12692
4	17.40	17.46	12688	12359
5	18.50	18.93	12692	12688
6	20.20	20.27	12692	12692
7	20.20	20.27	12692	12692
8	9.60	9.63	9944	695
9	8.30	8.33	8500	103
10	10.90	10.94	11101	1590
11	15.40	15.46	12594	9152
12	19.60	19.67	12692	12692
13	19.60	19.67	12692	12692
14	20.30	20.37	12692	12692
15	25.20	25.29	12692	12692
16	18.90	18.97	12692	12689
17	18.20	18.27	12691	12678
18	17.80	17.87	12690	12666
19	17.80	17.87	12690	12666
20	17.80	17.87	12690	12666

21	15.30	15.36	12586	8865
22	10.40	10.44	10689	1185
23	20.10	20.17	12692	12692
24	19.80	19.87	12692	12692
25	19.70	19.77	12692	12692
26	20.60	20.68	12692	12692
27	18.40	18.47	12692	12687
28	18.40	18.47	12692	12687
29	28.20	28.30	12692	12692
30	23.50	23.59	12692	12692

ACTUAL CATCH

MEAN = 18.93
ST.DEV = 4.25
CV = .2246
CU = 82.3%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 4.27
CV = .2246
CU = 82.3%

YIELD WITH RAINFALL

MEAN = 12427
CV = .0647

YIELD WITHOUT RAINFALL

MEAN = 11194
CV = .3246

50% DEPLETION SCHEDULE

SYSTEM CV .2643

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	35.40	29.56	12692	12692
2	42.50	35.49	12692	12692
3	50.20	41.92	12692	12692
4	28.10	23.47	12692	12692
5	16.80	14.03	12420	7065
6	17.20	14.36	12458	7496
7	21.30	17.79	12690	12663
8	21.30	17.79	12690	12663
9	21.30	17.79	12690	12663
10	23.50	19.63	12692	12692
11	22.20	18.54	12692	12687
12	18.60	15.53	12600	9196
13	19.50	16.29	12671	10594
14	19.50	16.29	12671	10594
15	19.50	16.29	12671	10594
16	19.50	16.29	12671	10594
17	20.40	17.04	12686	11651
18	20.40	17.04	12686	11651
19	21.30	17.79	12690	12663
20	22.20	18.54	12692	12687

21	24.50	20.46	12692	12692
22	25.20	21.05	12692	12692
23	20.30	21.96	12692	12692
24	21.30	17.79	12690	12663
25	22.20	18.54	12692	12687
26	30.20	25.22	12692	12692
27	9.10	7.60	7620	85
28	21.90	18.29	12692	12679
29	35.80	29.90	12692	12692
30	22.60	18.87	12692	12690

GENERATED CATCH		ADJUSTED CATCH	
MEAN	= 22.75	MEAN	= 19.00
ST.DEV	= 6.01	ST.DEV	= 5.02
CV	= .2643	CV	= .2643
CU	= 78.9%	CU	= 78.9%

YIELD WITH RAINFALL		YIELD WITHOUT RAINFALL	
MEAN	= 12386	MEAN	= 11396
CV	= .0957	CV	= .2662

50% DEPLETION SCHEDULE

SYSTEM CV .2908

FACTOR	ACTUAL CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	22.35	16.28	12670	10589
2	53.08	38.67	12692	12692
3	23.62	17.21	12687	11975
4	20.07	14.62	12490	7880
5	18.80	13.70	12392	6905
6	20.32	14.80	12512	7998
7	22.35	16.28	12671	10589
8	19.56	14.25	12445	7424
9	20.07	14.62	12490	7880
10	19.81	14.43	12467	7527
11	22.35	16.28	12670	10589
12	24.13	17.58	12689	12384
13	21.08	15.36	12586	8865
14	45.72	33.31	12692	12692
15	19.05	13.88	12405	6981
16	18.29	13.32	12367	5971
17	27.43	19.98	12692	12692
18	23.37	17.03	12686	11649
19	20.57	14.99	12536	8380
20	25.91	18.88	12692	12690

21	28.70	20.91	12692	12692
22	27.69	20.17	12692	12692
23	26.92	19.61	12692	12692
24	26.42	19.25	12692	12691
25	24.64	17.95	12690	12669
26	27.18	19.80	12692	12692
27	28.19	20.54	12692	12692
28	27.69	20.17	12692	12692
29	45.72	33.31	12692	12692
30	15.49	11.28	11514	2082

ACTUAL CATCH

MEAN = 26.08
ST.DEV = 7.58
CV = .2908
CU = 76.8%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 5.53
CV = .2908
CU = 76.8%

YIELD WITH RAINFALL

MEAN = 12564
CV = .0233

YIELD WITHOUT RAINFALL

MEAN = 10709
CV = .2908

50% DEPLETION SCHEDULE

SYSTEM CV .3323

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	24.60	25.69	12692	12692
2	30.10	31.44	12692	12692
3	15.90	16.61	12683	11023
4	14.30	14.94	12529	8082
5	7.60	7.94	7844	97
6	8.20	8.56	8676	109
7	24.60	25.69	12692	12692
8	20.30	21.24	12692	12692
9	21.90	22.87	12692	12692
10	9.60	10.03	10262	932
11	8.30	8.67	8227	114
12	18.70	19.53	12692	12692
13	19.50	20.37	12692	12692
14	19.50	20.37	12692	12692
15	14.40	15.04	12543	8412
16	14.30	14.94	12529	8082
17	23.60	24.65	12692	12692
18	23.00	24.02	12692	12692
19	23.60	24.65	12692	12692
20	17.50	18.28	12691	12678

21	17.60	18.38	12691	12681
22	18.40	19.22	12692	12690
23	8.30	8.67	8727	114
24	9.22	9.61	9935	683
25	15.30	15.98	12641	10122
26	15.60	16.29	12671	10594
27	25.60	26.74	12692	12692
28	119.60	20.47	12692	12692
29	17.40	18.17	12691	12675
30	31.10	32.48	12692	12692

ACTUAL CATCH		ADJUSTED CATCH	
MEAN	= 18.19	MEAN	= 19.00
ST.DEV	= 6.04	ST.DEV	= 6.31
CV	= .3323	CV	= .3323
CU	= 73.6%	CU	= 73.6%

YIELD WITH RAINFALL		YIELD WITHOUT RAINFALL	
MEAN	= 12075	MEAN	= 9997
CV	= .1128	CV	= .4544

50% DEPLETION SCHEDULE

SYSTEM CV .3891

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	36.90	29.91	12692	12692
2	63.20	51.23	12692	12692
3	56.80	46.04	12692	12692
4	42.60	34.53	12692	12692
5	38.30	31.04	12692	12692
6	35.20	28.53	12692	12692
7	25.40	20.59	12692	12692
8	28.60	23.18	12692	12692
9	29.30	23.75	12692	12692
10	9.20	7.46	7580	76
11	11.60	9.40	9517	596
12	12.70	10.29	10646	1107
13	21.50	17.43	12688	12266
14	21.50	17.43	12688	12266
15	21.50	17.43	12688	12266
16	18.40	14.91	12525	8063
17	19.60	15.89	12632	9840
18	20.20	16.37	12680	10629
19	20.20	16.37	12680	10629
20	26.30	21.32	12692	12692

21	24.50	19.86	12692	12692
22	24.50	19.86	12692	12692
23	23.80	19.29	12692	12691
24	19.40	15.72	12616	9536
25	12.30	9.97	10266	895
26	9.70	7.86	7822	90
27	18.50	15.00	12537	8130
28	30.40	24.64	12692	12692
29	40.20	32.58	12692	12692
30	33.50	27.15	12692	12692

GENERATED CATCH		ADJUSTED CATCH	
MEAN	= 23.44	MEAN	= 19.00
ST.DEV	= 9.12	ST.DEV	= 7.39
CV	= .3891	CV	= .3891
CU	= 68.9%	CU	= 68.9%

YIELD WITH RAINFALL		YIELD WITHOUT RAINFALL	
MEAN	= 12029	MEAN	= 9602
CV	= .1210	CV	= .4694

50% DEPLETION SCHEDULE

SYSTEM CV .4177

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	3.40	3.87	4869	0
2	5.60	6.38	6517	0
3	23.10	26.31	12692	12692
4	19.30	21.98	12692	12692
5	18.30	20.84	12692	12692
6	18.40	20.96	12692	12692
7	17.20	19.59	12692	12692
8	17.20	19.59	12692	12692
9	20.60	23.46	12692	12692
10	8.20	9.34	9475	547
11	8.20	9.34	9475	547
12	0.00	0.00	2859	0
13	12.00	13.67	12389	6845
14	19.30	21.98	12692	12692
15	25.00	28.48	12692	12692
16	10.70	12.19	12227	3493
17	11.20	12.76	12298	5160
18	14.20	16.17	12659	10515
19	10.80	12.30	12245	4506
20	26.10	29.73	12692	12692

21	20.00	22.78	12692	12692
22	16.50	18.79	12692	12692
23	19.20	21.87	12692	12692
24	20.60	23.46	12692	12692
25	6.30	7.18	7359	68
26	8.20	9.34	9475	547
27	15.40	17.54	12688	12375
28	19.00	21.64	12692	12692
29	28.00	31.89	12692	12692
30	26.10	29.73	12692	12692

GENERATED CATCH

MEAN = 16.68
ST.DEV = 6.97
CV = .4854
CU = 61.1%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 7.93
CV = .4854
CU = 61.1%

YIELD WITH RAINFALL

MEAN = 11724
CV = .1802

YIELD WITHOUT RAINFALL

MEAN = 9176
CV = .5483

50% DEPLETION SCHEDULE

SYSTEM CV .4430

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	33.10	28.72	12692	12692
2	48.20	41.82	12692	12692
3	52.50	45.55	12692	12692
4	8.40	7.29	7488	71
5	6.30	5.47	6008	0
6	28.60	24.81	12692	12692
7	13.20	11.45	11776	2383
8	16.80	14.57	12483	7611
9	16.80	14.57	12483	7611
10	15.90	13.79	12399	6950
11	0.00	0.00	2859	0
12	24.90	21.60	12692	12692
13	23.20	20.13	12692	12692
14	26.70	23.16	12692	12692
15	18.80	16.31	12673	10602
16	13.60	11.80	11949	2808
17	19.50	16.92	12685	11621
18	19.50	16.92	12685	11621
19	20.10	17.44	12688	12268
20	20.10	17.44	12688	12268

21	13.80	11.97	12182	3038
22	14.60	12.66	12285	5022
23	* 25.30	21.95	12692	12692
24	26.20	22.73	12692	12692
25	15.40	13.36	12371	6003
26	23.40	20.30	12692	12692
27	8.70	7.55	7599	83
28	42.60	36.96	12692	12692
29	30.40	26.37	12692	12692
30	35.20	30.54	12692	12692

GENERATED CATCH

MEAN = 21.90
ST.DEV = 9.70
CV = .4430
CU = 64.4%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 8.41
CV = .4430
CU = 64.4%

YIELD WITH RAINFALL

MEAN = 11933
CV = .1676

YIELD WITHOUT RAINFALL

MEAN = 9268
CV = .4911

50% DEPLETION SCHEDULE

SYSTEM CV .5175

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	1.30	1.12	3121	0
2	9.20	7.96	7852	97
3	13.50	11.69	11921	2658
4	25.70	22.25	12692	12692
5	14.30	12.38	12255	4612
6	14.30	12.38	12255	4612
7	12.00	10.39	10674	1148
8	19.10	16.53	12682	10987
9	14.50	12.55	12272	4913
10	17.80	15.41	12590	8901
11	21.50	18.61	12692	12688
12	0.00	0.00	2859	0
13	14.80	12.81	12304	5216
14	18.00	15.58	12605	9229
15	19.10	16.53	12682	10987
16	27.70	23.98	12692	12692
17	22.40	19.39	12692	12691
18	14.20	12.29	12244	4495
19	14.90	12.90	12315	5293
20	22.40	19.39	12692	12691

21	23.40	20.26	12692	12692
22	28.20	24.41	12692	12692
23	6.30	5.45	5999	0
24	22.40	19.39	12692	12691
25	18.00	15.58	12605	9229
26	26.70	23.11	12692	12692
27	9.20	7.96	7852	97
28	36.10	31.25	12692	12692
29	26.50	22.94	12692	12692
30	53.20	46.05	12692	12692

GENERATED CATCH

MEAN = 21.95
ST.DEV = 11.36
CV = .5175
CU = 58.7%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 9.81
CV = .5175
CU = 58.7%

YIELD WITH RAINFALL

MEAN = 11677
CV = .1998

YIELD WITHOUT RAINFALL

MEAN = 9058
CV = .5230

50% DEPLETION SCHEDULE

SYSTEM CV .5175

FACTOR	ACTUAL CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)	YIELD W/O RAIN (KG/HA)
1	1.27	1.01	3088	0
2	9.14	7.26	7417	71
3	13.46	10.69	10752	1378
4	25.65	20.37	12692	12692
5	14.48	11.50	11788	2476
6	14.48	11.50	11788	2476
7	11.94	9.48	9765	556
8	19.05	15.12	12554	8464
9	14.48	11.50	11788	2476
10	17.78	14.12	12430	7313
11	21.59	17.14	12686	11677
12	0.00	0.00	2859	0
13	14.73	11.69	11921	2658
14	18.03	14.31	12452	7433
15	19.05	15.12	12554	8464
16	23.37	18.55	12692	12687
17	19.05	15.12	12554	8464
18	27.69	21.98	12692	12692
19	22.35	17.74	12689	12661
20	14.22	11.29	11516	2163

21	4.83	3.83	4581	0
22	22.35	17.74	12689	12661
23	23.37	18.55	12692	12687
24	28.19	22.38	12692	12692
25	28.96	22.99	12692	12692
26	26.67	21.17	12692	12692
27	13.46	10.69	10752	1378
28	36.07	28.64	12692	12692
29	26.42	20.98	12692	12692
30	67.56	53.64	12692	12692

ACTUAL CATCH

MEAN = 23.93
ST.DEV = 13.89
CV = .5802
CU = 53.7%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 11.03
CV = .5802
CU = 53.7%

YIELD WITH RAINFALL

MEAN = 11735
CV = .1938

YIELD WITHOUT RAINFALL

MEAN = 8959
CV = .5484

60% DEPLETION SCHEDULE

SYSTEM CV .1681

FACTOR	ACTUAL CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)
1	65.71	48.90	12692
2	61.29	45.61	12692
3	40.31	30.00	12692
4	34.80	25.90	12692
5	34.80	25.90	12692
6	34.80	25.90	12692
7	33.10	24.63	12692
8	32.03	23.84	12692
9	25.90	19.27	12689
10	29.82	22.19	12691
11	27.10	20.17	12690
12	28.16	20.98	12690
13	25.90	19.27	12689
14	25.40	18.90	12688
15	25.40	18.90	12688
16	24.30	18.08	12685
17	25.90	19.27	12689
18	25.9	19.27	12689
19	25.90	19.27	12689
20	23.74	17.68	12683

21	24.85	18.49	12686
22	24.85	18.49	12686
23	24.80	18.46	12686
24	22.09	16.44	12596
25	22.64	16.85	12640
26	23.74	17.67	12683
27	22.64	16.85	12640
28	21.53	16.02	12535
29	24.85	18.49	12686
30	25.40	18.90	12688

ACTUAL CATCH

MEAN = 25.53
ST.DEV = 4.29
CV = .1681
CU = 86.6%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 3.19
CV = .1681
CU = 86.6%

YIELD WITH RAINFALL

MEAN = 12688
CV = .0033

60% DEPLETION SCHEDULE

SYSTEM CV .2643

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)
1	35.4	29.56	12692
2	42.50	35.49	12692
3	50.20	41.92	12692
4	28.1	23.47	12692
5	16.80	14.03	12183
6	17.20	14.36	12247
7	21.30	17.79	12684
8	21.30	17.79	12684
9	21.30	17.79	12684
10	23.50	19.63	12689
11	22.2	18.54	12689
12	18.6	15.53	12453
13	19.50	16.29	12576
14	19.50	16.29	12576
15	19.50	16.29	12576
16	19.50	16.29	12576
17	20.40	17.04	12645
18	20.40	17.04	12645
19	21.30	17.79	12684
20	22.20	18.54	12687

21	24.50	20.46	12690
22	25.20	21.05	12690
23	26.3	17.79	12684
24	21.30	17.79	12684
25	22.20	18.54	12687
26	30.20	25.22	12692
27	9.1	7.6	7642
28	21.9	18.29	12686
29	35.8	29.90	12692
30	22.60	18.87	12687

ACTUAL CATCH		ADJUSTED CATCH	
MEAN	= 22.75	MEAN	= 19.00
ST.DEV	= 6.01	ST.DEV	= 5.02
CV	= .2643	CV	= .2643
CU	= 78.9%	CU	= 78.9%

YIELD WITH RAINFALL

MEAN = 12360
CV = .0951

60% DEPLETION SCHEDULE

SYSTEM CV .2908

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)
1	22.35	16.28	12575
2	53.08	38.67	12692
3	23.62	17.21	12271
4	20.07	14.62	12290
5	18.80	13.70	12121
6	20.32	14.80	12330
7	22.35	16.28	12575
8	19.56	14.25	12226
9	20.07	14.62	12290
10	19.81	14.43	12260
11	22.35	16.28	12575
12	24.13	17.58	12683
13	21.08	15.36	12426
14	45.72	33.31	12692
15	19.05	13.88	12154
16	18.29	13.32	12060
17	27.43	19.98	12689
18	23.37	17.03	12653
19	20.57	14.99	12371
20	25.91	18.88	12688

21	28.70	20.91	12690
22	27.69	20.17	12690
23	26.92	19.61	12689
24	26.42	19.25	12689
25	24.64	17.95	12685
26	27.18	19.80	12689
27	28.19	20.54	12690
28	27.69	20.17	12690
29	45.72	33.31	12692
30	15.49	11.28	10706

ACTUAL CATCH		ADJUSTED CATCH	
MEAN	= 26.08	MEAN	= 19.00
ST.DEV	= 7.58	ST.DEV	= 5.53
CV	= .2908	CV	= .2908
CU	= 76.8%	CU	= 76.8%

YIELD WITH RAINFALL

MEAN = 12484
CV = .0399

60% DEPLETION SCHEDULE

SYSTEM CV .3891

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)
1	36.90	29.91	12692
2	63.20	51.23	12692
3	56.80	46.04	12692
4	42.60	34.53	12692
5	38.30	31.04	12692
6	35.20	28.53	12692
7	25.40	20.59	12690
8	28.60	23.18	12692
9	29.30	23.75	12692
10	9.20	7.46	7595
11	11.60	9.40	8877
12	12.70	10.29	9779
13	21.50	17.43	12682
14	21.50	17.43	12682
15	21.50	17.43	12682
16	18.40	14.91	12356
17	19.60	15.89	12513
18	20.20	16.37	12586
19	20.20	16.37	12586
20	26.30	21.32	12691

21	24.50	19.86	12689
22	24.50	19.86	12689
23	23.80	19.29	12689
24	19.40	15.72	12484
25	12.30	9.97	9717
26	9.70	7.86	7879
27	18.50	15.00	12372
28	30.40	24.64	12692
29	40.20	32.58	12692
30	33.50	27.15	12692

GENERATED CATCH

MEAN = 23.44
ST.DEV = 9.12
CV = .3891
CU = 68.9%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 7.39
CV = .3891
CU = 68.9%

YIELD WITH RAINFALL

MEAN = 11926
CV = .1282

60% DEPLETION SCHEDULE

SYSTEM CV .4430

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)
1	33.10	28.72	12692
2	48.20	41.82	12692
3	52.50	45.55	12692
4	8.40	7.29	7298
5	6.30	5.47	5367
6	28.60	24.81	12692
7	13.20	11.45	10735
8	16.80	14.57	12284
9	16.80	14.57	12284
10	15.90	13.79	12138
11	0.00	0.00	2859
12	24.90	21.60	12691
13	23.20	20.13	12690
14	26.70	23.16	12692
15	18.80	16.31	12578
16	13.60	11.80	11619
17	19.50	16.92	12646
18	19.50	16.92	12646
19	20.10	17.44	12682
20	20.10	17.44	12682

21	13.80	11.97	11648
22	14.60	12.66	11961
23	25.30	21.95	12691
24	26.20	22.73	12691
25	15.40	13.36	12066
26	23.40	20.30	12690
27	8.70	7.55	7616
28	42.60	36.96	12692
29	30.40	26.37	12692
30	35.20	30.54	12692

GENERATED CATCH

MEAN = 21.90
ST.DEV = 9.70
CV = .4430
CU = 64.4%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 8.41
CV = .4430
CU = 64.4%

YIELD WITH RAINFALL

MEAN = 11823
CV = .1706

60% DEPLETION SCHEDULE

SYSTEM CV .2643

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)
1	1.30	1.12	3098
2	9.20	7.96	7933
3	13.50	11.69	11450
4	25.70	22.25	12691
5	14.30	12.38	11911
6	14.30	12.38	11911
7	12.00	10.39	9777
8	19.10	16.53	12609
9	14.50	12.55	11942
10	17.80	15.41	12434
11	21.50	18.61	12687
12	0.00	0.00	2859
13	14.80	12.81	11983
14	18.00	15.58	12461
15	19.10	16.53	12609
16	27.70	23.98	12692
17	22.40	19.39	12689
18	14.20	12.29	11895
19	14.90	12.90	11994
20	22.40	19.39	12689

21	23.40	20.26	12690
22	28.20	24.41	12692
23	6.30	5.45	5357
24	22.40	19.39	12689
25	18.00	15.58	12461
26	26.70	23.11	12692
27	9.20	7.96	7933
28	36.10	31.25	12692
29	26.50	22.94	12691
30	53.20	46.05	12692

GENERATED CATCH		ADJUSTED CATCH	
MEAN	= 21.95	MEAN	= 19.00
ST.DEV	= 11.36	ST.DEV	= 9.81
CV	= .5175	CV	= .5175
CU	= 58.7%	CU	= 58.7%

YIELD WITH RAINFALL

MEAN = 11584
CV = .2073

60% DEPLETION SCHEDULE

SYSTEM CV .5802

FACTOR	GENER. CATCH (MM)	ADJ.CATCH (MM)	YIELD W/RAIN (KG/HA)
1	1.27	1.01	3044
2	9.14	7.26	7349
3	13.46	10.69	10056
4	25.65	20.37	12690
5	14.48	11.50	11037
6	14.48	11.50	11037
7	11.94	9.48	8901
8	19.05	15.12	12389
9	14.48	11.50	11037
10	17.78	14.12	12201
11	21.59	17.14	12664
12	0.00	0.00	2859
13	14.73	11.69	11450
14	18.03	14.31	12238
15	19.05	15.12	12389
16	23.37	18.55	12687
17	19.05	15.12	12389
18	27.69	21.98	12691
19	22.35	17.74	12684
20	14.22	11.29	10707

21	4.83	3.83	4013
22	22.35	17.74	12684
23	23.37	18.55	12687
24	28.19	22.38	12691
25	28.96	22.99	12691
26	26.67	21.17	12691
27	13.46	10.69	10056
28	36.07	28.64	12692
29	26.42	20.98	12690
30	67.56	53.64	12692

ACTUAL CATCH

MEAN = 23.93
ST.DEV = 13.89
CV = .5802
CU = 53.7%

ADJUSTED CATCH

MEAN = 19.00
ST.DEV = 11.03
CV = .5802
CU = 53.7%

YIELD WITH RAINFALL

MEAN = 11532
CV = .2106

REFERENCES

Bartholic, J.F. ed. 1983. Impact Evaluation of Increased Water Use by Agriculture in Michigan. MSU Ag. Expt. Sta. Research Report No. 449. East Lansing, MI.

Benami, A. and F. R. Hore. 1964. A New Irrigation Sprinkler Distribution Coefficient. Transactions of the ASAE 7:157-158.

Blaney, H.F. and W.D. Criddle. 1950. A Method of Estimating Water Requirements in Irrigated Areas from Climatological DAta. USDA-SCS mimeo.

Bralts, Vincent F. and Charles D. Kesner. 1983. Drip Irrigation Field Uniformity Estimation. Transactions of the ASAE Vol. 26:1369-1374.

Bralts, V.F. and K.A. Algozin. 1985. Report of Results for Irrigation System Evaluation and Demonstration Project. USDA.

Bralts, V.F. and Wu I. .1986. Drip Irrigation Design and Evaluation Based on the Statistical uniformity Concept. in: Advances in Irrigation Vol IV. D. Hillel ed. Academic Press, Orlando, FLA.

Bralts, V.F. 1897. Personal Communication.

Bresler E., G. Dagen and J. Hanks. 1982. Statistical Analysis of Crop Yield under Controlled Line Source Irrigation. Soil Science Society of America Journal 4.

Chang, A.C., R.W. Skaggs, L.F. Hermsmeir and W.R. Johnston .1983. Evaluation of a Water Management Model for Irrigated Agriculture. Transactions of the ASAE 26:2.

Chaudry, F.H. 1976. Sprinkler Uniformity Measures and Skewness. Journal of Irrigation and Drainage Division ASCE 102 (Ir4)

Chaudry, F.H. 1978. Nonuniform Sprinkler Application Efficiency. Journal of Irrigation and Drainage Division ASCE 104 (IR2)

Childs, S.W. and R.J. Hanks. 1975. Model of Soil Salinity Effects on Crop Growth. Proc. Soil Sci. Soc. Am. 39:617-622.

Childs, S.W., J.R. Gilley and W.E. Splinter. 1977. A Simplified Model of Corn Growth Under Moisture Stress. Transactions of the ASAE 20(5):858-865.

Christiansen, J.E. 1942. Irrigation by Sprinkling. California Agricultural Expt. Sta. Bulletin 670, Univ. of Calif., Berkeley, CA.

Dabbous, B.J. 1962. A Study of Sprinkler Uniformity Evaluation Methods. Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science, Utah State Univ., Logan, Utah.

Dent, J.B. and M.J. Blackie. 1979. Systems Simulation in Agriculture. Applied Science Publishers Ltd., Essex, G.B.

Doorenbos, J. and A. H. Kassam. 1979. Yield Response to Water. FAO Irrigation and Drainage Paper NO. 33. FAO, Rome, Italy.

Doorenbos, J. and W.O. Pruitt. 1977. Crop Water Requirements FAO Irrigation and Drainage Paper 24. FAO, Rome, Italy.

Driscoll, M.A., and V.F. Bralts. 1986. Report of Results for Irrigation System Evaluation and Scheduling Demonstration Project. USDA.

Duncan, W.G. 1975. MAIZE in: Crop Physiology. L.T. Evans, ed. Cambridge University Press, London, G.B.

Elliott, R.L., J.D. Nelson, J.C. Loftis and W.E. Hart. 1979. Statistical Distributions of Sprinkler Application Depths. ASAE paper No. 79-2081, ASAE, St. Joseph, Mi.

Elliott, R.L., J.D. Nelson, J.C. Loftis and W.E. Hart. 1980. Comparison of Sprinkler Uniformity Models. Journal of Irrigation and Drainage Division ASCE 106(IR4) .

English, M.J. 1981. The Uncertainty of Crop Models in Irrigation Optimization. Transactions of the ASAE 24:4.

English, M.J. and G.S. Nuss 1982. Designing for Deficit Irrigation. Journal of Irrigation and Drainage Division ASCE 108 (IR2)

English, M.J., L.D. James, D.J. Hunsaker, and R.J. McKusick 1985. A practical View of Deficit Irrigation. ASAE Paper No. 85-2595. ASAE, St. Joseph, MI.

________ (1983) Estimating Agricultural Crop Water Requirements. Technical Guideline for the Bureau of Reclamation. Division of Planning and Technical Services Hydrology Branch Water Utilization Section, Engineering and Research Center, Denver, CO.

Feinerman, E., J. Letey and H.J. Vaux Jr. 1983. The Economics of Irrigation with Nonuniform Infiltration. Water Resources Research 19:6.

Fienerman, E., K.C. Knapp and J. Letey. 1984. Salinity and Uniformity of Water Infiltration as Factors in Yield and Economically Optimal Water Application. Soil Science Society of America Journal Vol.48:477-481.

Gurovich, L.A. 1979. Effects of Improved Field Practice on Crop Yield, Water Use and Profitability of Irrigation in Central Chile. Irrigation Science 1.

Gurovich, L.A. and H.R. Duke. 1984. Economic Effects of Spatial Distribution Patterns for Water Application Under Center Pivot Systems. ASAE Paper No. 84-2584.

Hanks, R.J. 1974. Model for Predicting Yield as Influenced by Water Use. Agronomy Journal Vol. 66:660-664.

Hanson, B.R. and W.W. Wallender. 1985. Bidirectional Uniformity of Water Applied by Continuous Move Sprinkler Machines. ASAE. Paper No. 85-2572 ASAE, St. Joseph, MI.

Hardjoamidjojo, S. R.W. Skaggs and G.O. Schwab. 1982. Corn Yield Response to Excessive Soil Water Conditions. Transactions of the ASAE Vol. 25:922-927.

Hart, W.E. 1961. Overhead Irrigation Pattern Parameters. Agricultural Engineering. 42:354-355.

Hart,W.E., G. Peri and G.V. Skogerboe .1979. Irrigation Performance: An Evaluation. Journal of the Irrigation and Drainage Division of the ASCE.

Hart, W.E. D.I. Norum and G. Peri. 1980. Optimal Seasonal Irrigation Application Analysis. Journal of Irrigation and Drainage Division ASCE 106(IR3)

Hart, W.E. and W.N. Reynolds. 1965. Analytical Design of Sprinkler Systems. Transactions of the ASAE 8(1):83-85,89.

Heerman,D.F. and P.R. Hein. 1968. Performance Characteristics of Self Propelled Center Pivot Sprinkler Systems. Transactions of the ASAE 11(1):11-15.

Heerman, D.F. and D.L. Swedensky. 1984. Simulation Analysis of Center Pivot Sprinkler Uniformity. ASAE Paper No. 84-2582. ASAE, St. Joseph, MI.

Hillel, Daniel and Y. Guron. 1973. Relation Between Evapotranspiration Rate and Maize Yield. Water Resources Research 9:3.

Hillel, D. Fundamentals of Soil Physics. 1980. Academic Press Inc., London, G.B.

Hill, R.W. and J. Keller. 1980. Irrigation System Selection for Maximum Crop Profit. Transactions of the ASAE 23(2):366-372.

Howell, D.T. 1964. Sprinkler Non-uniformity Characteristics and Yield. Journal of Irrigayion and Drainage Division ASCE 90(IR3)

Israelsen, O.W. and V.E. Hansen. 1962. Irrigation Principles and Practices. John Wiley and Sons, New York.

Jensen, M.E. D.C.N. Robb and G.E. Franzoy. 1970. Scheduling Irrigation Using Crop-Soil Data. Journal of the Irrigation and Drainage Division ASCE 96(IR1).

Jones, C.A. and J.R. Kiniry. 1986. CERES-Maize A Simulation of Maize Growth and Development. Texas A&M Univ. Press, College Station, TX.

Karmeli, D. 1977. Water Distribution Patterns for Sprinkler and Surface Irrigation Systems. Proc. National Conf. on Irrig. Return Flow Quality Management, Colo. State Univ, Fort Collins, Colorado, May 16-19, 1977

Karmeli, David (1978) Estimating Sprinkler Distribution Patterns Using Linear Regression. Transactions of the ASAE 21 (3)682-686.

Karmeli, D., L.J. Salazar and W.R. Walker. 1978. Assessing the Spatial Variability of Irrigation Water Applications. Document No. EPA-600/2-78-041, U.S. Environ. Prot. Agency, ADA, OK.

Karmeli,D. G. Peri and M. Todes. 1985. Irrigation Systems: Design and operation. Oxford University Press, Cape Town.

Kay, M. 1983. Sprinkler Irrigation Equipment and Practice. Batsford Academic and Educational Ltd., London, G.B.

Kruse, E.G. 1978. Describing Irrigation Efficiency and Uniformity. Journal of the Irrigation and Drainage Division ASCE 104(IR1).

Letey, J., H.J. Vaux Jr., and E. Fienerman 1984. Optimum Crop Water Application as Affected by Uniformity of Water Infiltration. Agronomy Journal 76: May-June.

Lynne, G.D. and R.R. Carriker. 1979. Crop Response Information for Water Institutions. Journal of Irrigation and Drainage Division ASCE 105 (IR3)

Marek, T.H., D.J. Undersander, and L.L. Ebeling. 1986. An Areal-Weighted Uniformity Coefficient for Center Pivot Irrigation Systems. Transactions of the ASAE 29(6):1665-1668.

Martin, D.L., D.G. Watts and J.R. Gilley. 1984. Model and Production Functions for Irrigation Management. Journal of Irrigation and Drainage Division ASCE 110 (IR2).

Morey, R.V., J.R. Gilley, F. G. Bergsrud and L.R. Dirkzwager 1980. Yield Response of Corn Related to Soil Moisture. Transactions of the ASAE 23:5.

Musick, J.T. and D.A. Dusek. 1980. Irrigated Corn Yield Response to Water. Transactions of the ASAE 23:1.

Norum, E.M. 1961. A Method of Evaluating the Adequacy and Efficiency of Overhead Irrigation Systems. ASAE Paper No. 61-206, ASAE, St. Joseph, MI.

Norum, Donald I., G. Peri and W.E. Hart. 1979. Application of System Optimal Depth Concept. Journal of the Irrigation and Drainage Division of the ASAE.

On-Farm Irrigation Committee of the Irrigation and Drainage Division, ASCE. 1978. Describing irrigation efficiency and uniformity. Journal of the Irrigation and Drainage Division of the ASCE.

Penman, H.L. 1948. Natural Evaporation from Open Water, Bare Soil and Grass. Proc. from the Royal Soc. Series A.

Peri, G., W.E. Hart and D.I. Norum. 1979. Optimal Irrigation Depths - a Method of Analysis. Journal of Irrigation and Drainage Division ASCE 105(IR4)

Seigner, Ido. 1978. A Note on the Economic Significance of Uniform Water Application. Irrigation Science 1.

Seigner, I. 1979. Irrigation Uniformity Related to Horizontal Extent of Root Zones Irrigation Science 1:89-96.

Seniwongse, C., I. Wu and W.N. Reynolds. 1972. The Effects of Skewness and Kurtosis on the Uniformity Coefficient and their Applications to Sprinkler Irrigation Design. Transactions of the ASAE 15(2):266-271.

Slabbers, P.J. V.S. Herrendorf and M. Stapper. 1979. Evaluation of Simplified Water-crop Yield Models. Agricultural Water Management 2:2

Solomon, Ken and Malcolm Kodoma. 1978. Center Pivot End Sprinkler Pattern Analysis and Selection. Transactions of the ASAE :

Solomon, Ken (1979) Variability of Sprinkler Coefficient of Uniformity Test Results. Transactions of the ASAE

Solomon, K.H. 1983. Irrigation Uniformity and Yield Theory. PhD Dissertation. Agricultural & Engineering Dept. Utah State Univ., Logan, Utah.

Solomon, K.H. 1984. Yield Related Interpretations of Irrigation Uniformity and Efficiency Measures. Irrigation Science 5:161-172.

Solomon, Kenneth H. 1985. Typical Crop Water Production Functions. ASAE Paper No. 85-2596 ASAE, St. Joseph, MI.

Stegman, E.C. L.H. Schiele and A. Bauer. 1976. Plant Water Stress Criteria for Irrigation Scheduling Transactions of the ASAE 19:5

Stern, Jack and Eshel Bresler. 1983. Nonuniform Sprinkler Irrigation and Crop Yield. Irrigation Science 4: 17-29

Su, M . 1979. Comparative Evaluation of Irrigation Uniformity Indices. Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science, Utah State Univ. Logan, Utah.

Tezar, E. 1971. Investigation into Distribution Uniformity of Water from Sprinkler Heads. Yearbook of the Fac. of Ag., Adana, Univ. of Ankara, Turkey, 1(1):63-87.

Tscheschke, P.D. and J.R. Gilley. 1979. Status and Verification of Nebraska's Corn Growth Model - CORNGRO. Transactions of the ASAE 22:1329-37

USDA-SCS 1982. South National Technical Center Note No. 707. USDA Soil Conservation Service, Fort Worth, TX.

Walker, W.R. 1979. Explicit Sprinkler Irrigation Uniformity: Efficiency Model. J. Irrig. and Drain. Div. ASCE 105(IR2):129-136.

Wilcox, J.C. and G.E. Swailes. 1947. Uniformity of Water Distribution by Some Under-Tree Orchard Sprinklers. Scientific Agriculture 27(11)565-583.

Varlev, I. 1976. Evaluation of Nonuniformity and Irrigation Yield. Irrigation and Drainage Division Journal ASCE 102(IR1).

von Bernuth, R.D. 1983. Nozzling Considerations for Center Pivots With End Guns. Transactions of the ASAE 26:419-422.

Warrick A.W. and W.R. Gardner. 1983. Crop Yield as Affected by Spatial Variations of Soil and Irrigation. Water Resources Research 19.

Wu, I.P. and H.M. Gitlin. 1983. Drip Irrigation Application Efficiency and Schedules. Transactions of the ASAE Vol 26:92-99.

Zaslavasky, D. and N Buras. 1967. Crop Response to Uniform Application of Irrigation Water. Transactions of the ASAE 10:96.