

**AUTOMATED WATER MANAGEMENT FOR CENTER PIVOT IRRIGATION
SYSTEMS**

BY

JARED K. OSWALD

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ABSTRACT**AUTOMATED WATER MANAGEMENT FOR CENTER PIVOT IRRIGATION
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Simulations were conducted to determine the effectiveness of a software package that fully automates center pivot irrigation systems on fields planted to corn, soybeans and potatoes for years 1986-2005. A total of seven sites from the Central and Northern Plains were chosen for analysis (Akron, CO, Ames, IA, Brookings, SD, Oakes, ND, Ord, NE, Rock Port, MO, and St. John, KS). System pumping capacities of 37.9, 50.5, and 63.1 liters/second were simulated at each site along with the soil available water holding capacities of 83, 125, and 167 mm/meter. The different combinations of pumping capacities and soil available water holding capacities resulted in a total of nine treatments at a given site per year. The software was able to schedule irrigations effectively using the ASCE Penman Monteith equation for estimating reference evapotranspiration (ET_r) throughout the growing season for all crop types simulated.

For corn, the Akron, CO site had the smallest average ratio of rainfall to crop evapotranspiration (ET_c) which resulted in the largest average number of days under minimum allowable soil water content per season (44 days, Treatment 7). In contrast, the Ames, Brookings, Oakes, Ord, and Rock Port sites all averaged five days or less below

the minimum allowable water content for all treatments with pumping rates of 50.5 or 63.1 L/s.

A yield model was used to determine if the minimum allowable water contents were set to a correct level for corn and to determine the overall effectiveness of the irrigation scheduling software. The minimum allowable balances were found to be set to the correct levels since relative yield decreased as the number of days below the minimum allowable level increased. This is evidenced at the St. John, KS site where Treatment 1 averaged 31 days below the minimum allowable balance with an average relative yield of 85% while Treatment 6 averaged one day below the minimum allowable balance with an average relative yield of 95%.

For the soybean simulations, Treatment 7 at Akron, CO averaged the greatest number of days below the minimum allowable balance of all the treatments at all the sites (37 days). At several of the sites (Ames, Brookings, Oakes, and Rock Port), the scheduling software was able to keep the average days below the minimum allowable balance for all treatments to five or less.

Due to the high setting of the minimum allowable water balance (70% of field capacity during the critical stage of development) and the shallow rooting depth, the average days below minimum allowable were greater for potatoes than corn and soybeans. The highest average number of days was Treatment 1 at the Akron site (45 days) and the lowest was Treatment 9 at Ames (one day).

Simulations were conducted using the Jensen-Haise equation to estimate corn ET_c at the Brookings and St. John sites. The data from these simulations were then compared

to the simulations conducted at the same sites using the ASCE Penman Monteith equation. The average relative yield for all treatments was identical regardless of the method used to determine ET at the Brookings site. At St. John, the relative yield increased an average of 3% when using the Jensen-Haise equation.

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LIST OF ABBREVIATIONS

ASCE	American Society of Civil Engineers
AW	percentage of available soil water
CGDD	cumulative growing degree days
CS _{dj}	crop susceptibility factors for drought water conditions for growth period <i>j</i>
DBM	days below minimum
DPE	days past emergence
DPP	days past planting
e_a	mean actual vapor pressure
e_s	saturation vapor pressure
$e_s - e_a$	saturation vapor pressure deficit
ET	evapotranspiration
ET _c	crop evapotranspiration
ET _p	potential evapotranspiration
ET _r	reference evapotranspiration
FAO	Food and Agriculture Organization
G	soil heat flux density at the soil surface
GDD	growing degree days
JH	Jensen-Haise
K _a	plant available water coefficient
K _c	crop coefficient
PM	Penman Monteith

R_n	calculated net radiation at the crop surface
R_s	solar radiation
SD_{dj}	stress-day factor for drought conditions for growth period j
SDI_d	stress day index for drought conditions
SIS	scientific irrigation scheduling
T_m	mean daily air temperature
u_2	mean daily wind speed at 2-m height
WHC	water holding capacity
Y	yield
Y_m	maximum yield under the conditions of ET_m
YR_d	overall relative yield as a percent
YR_d	relative yield from drought stress as a percent
γ	psychrometric constant
Δ	slope of the saturation vapor pressure-temperature curve

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CHAPTER I

INTRODUCTION AND OBJECTIVES

Center pivots irrigate more than 8 million hectares in the United States (Werner, 2000). The popularity of these systems can be attributed to their ease of use and relative high application efficiencies compared to other forms of irrigation. Generally, center pivots are considered to have 80-90% water application efficiency compared to surface irrigation systems which are generally considered to have an application efficiency of 50-60%. This can translate into significant water savings throughout the growing season as shown by Werner and Krautschun (2003) in which they found a 75% water use reduction when utilizing a center pivot compared to surface irrigation.

To achieve the greatest yield return from a center pivot irrigation system while efficiently using water resources and energy, scientific irrigation scheduling must be used (Field et al., 1988, Shae et al., 1999, Heinemann et al., 2000, Steele et al., 2000). Scientific irrigation scheduling uses the soil water holding capacity (WHC), crop water use, and minimum allowable soil water depletions to determine the timing and depth of the irrigation application. In a Steele et al. study in 2000, they were able to save 30% in irrigation inputs (water and energy) while increasing yield 5% using scientific scheduling compared with grower practices.

Irrigation scheduling is most often based on past practice instead of scientific inputs due to limitations in time, training, and experience. Lieb et al. (2002) found that as

of 1998, as few as 18% of irrigators used scientific scheduling, even with consultants available for technical support.

Complete automation of irrigation has been accomplished on solid-set and drip irrigation systems. A daily evapotranspiration (ET) deficit is determined using data from a nearby weather station. This deficit is then replenished on an as needed basis after accounting for rainfall. Solid-set and drip irrigation systems may be capable of irrigating the entire field in a single day. Center pivots, however, do not cover the entire field in a single day. Hence, the challenge to scheduling center pivot irrigations is being able to apply an adequate amount of water at the correct time in order to eliminate a future deficit. It is also imperative not to water excessively which can cause transport of nutrients out of the crop root zone, wasted pumping energy, and of course, wasted water.

In the past, control of center pivots was performed from the panel located at the pivot point in the center of the field. In order for the farmer to know the status of an individual center pivot or to change settings, a trip to the field was required. Technological developments allow the farmer to view the status of all their pivots on-line along with being able to change settings such as direction, speed, etc. This saves the time and energy costs required to travel to the field. This technology, coupled with irrigation scheduling software and in-field weather stations, will also relieve the farmer of the daily tedium of scheduling irrigations.

The objectives of this project were:

1. To create a crop specific irrigation scheduling software package to relieve the producer of the daily tedium of scheduling irrigation.
2. Test the irrigation scheduling software using a simulator for various crops, pumping rates, and soil water holding capacities with weather data collected at sites throughout the upper Great Plains.
3. Determine the effectiveness of the irrigation scheduling software in preventing yield reduction for corn.
4. Determine the effect that increased pumping rate has on the number of days below the minimum allowable balance for a given soil type at a particular site.

CHAPTER II

LITERATURE REVIEW

2.1 Evapotranspiration Equations

The concept of scientific irrigation scheduling (SIS) has been around for a long time. Commonly, scientific scheduling utilizes weather data input into an evapotranspiration (ET) equation, soil moisture measurements, or a combination of the two to estimate the soil water balance in the field and determine the timing and depth of the irrigation application.

There are several theoretical equations available to estimate the ET over a specified surface. Howard Penman (1948), an English physicist, derived an equation that uses the combination of energy balance along with an empirical aerodynamic expression to estimate the ET from a surface. John Monteith (1965), a researcher from England, replaced Penman's empirically based aerodynamic expression with a more theoretically based equation that incorporated the combined effects of aerodynamic and surface resistance. This equation, referred to as the Penman-Monteith (PM), was the basis for many future adaptations.

Wright and Jensen (1972) and Wright (1982) developed adaptations, commonly referred to as the "Kimberly-Penman" equations, which allowed the Penman equation to be referenced to an alfalfa crop. The Food and Agriculture Organization (FAO) of the United Nations published the FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1977) which outlined a procedure and equation for calculating reference and crop ET. The equation was then updated by Allen et al. (1998) and presented as the FAO-56.

This equation, referred to commonly as the FAO Penman-Monteith, has a reference surface defined as "...a hypothetical crop with an assumed height of 0.12 m, with a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered." The American Society of Civil Engineers (ASCE) also developed its own form of the PM equation published in ASCE Manual 70 (Jensen et al., 1990). More recently in 2005, the ASCE adopted a "Standardized Reference Evapotranspiration Equation" (Allen et al.) It is commonly referred to as the ASCE Penman-Monteith and is nearly identical in form to the FAO version except that it contains interchangeable constants that can be used to reference either a 0.12 m tall grass or 0.5 m tall alfalfa.

There have also been several empirical equations developed to estimate ET. Thornthwaite correlated mean air temperature with ET (Thornthwaite, 1948, Thornthwaite and Mather, 1955). Hargreaves and Samani (1982, 1985) developed an equation for estimating ET using eight years of lysimeter data collected from cool-season Alta fescue grass in Davis, California. Jensen and Haise (1963) developed an equation based on inputs of solar radiation and mean air temperature.

Jensen et al. (1990) reviewed 13 of the most commonly used equations of that time in the process of finding a standardized method for calculation of ET. The ET estimates determined by the individual equations were compared to weighing lysimeter data collected from three different sites in the United States. Jensen then ranked the methods by their perceived effectiveness compared to the lysimeter. He found the Penman-Monteith equation ranked first among the methods analyzed. The study ranked

many of the Penman based equations higher than the empirically based non-Penman equations.

2.2 Crop Coefficients

The reference ET (ET_r) value, determined by the equations presented above, is multiplied by a crop coefficient (K_c) that accounts for the effects of the crop characteristics on the crop water demand.

Many studies have been conducted that developed different K_c curves for a given ET equation, season length, and crop type. They are often represented as seasonal crop curves which are a function of days past planting (DPP) or days past emergence (DPE). Doorenbos and Pruitt (1977) developed K_c values for a variety of different crops which were to be used with the Blaney-Criddle, Radiation, Penman, or Pan Evaporation method of determining ET_r . A fourth order polynomial was developed specifically for the Jensen-Haise equation in Southeast North Dakota based on DPE (Stegman et al., 1977). Wright (1981) developed a set of mean crop coefficients for use with alfalfa reference ET equations. Wright (1982) developed a set of basal crop coefficients to be used with an alfalfa reference ET equation. These new coefficients were to be implemented when soil evaporation was minimal but the moisture in the root zone is adequate. The coefficients proposed by Wright were further modified by Jensen et al. (1990) based on personal communications between the two researchers. Allen et al. (1998) developed K_c values to be used with the FAO Penman equation, which is a grass reference ET equation.

Many researchers have proposed making K_c curves a function of growing degree days instead of a calendar day method. These studies often explore adapting crop curves developed for a specific climate or region, to another. A third order polynomial was developed to adapt DPP crop coefficients for a modified Penman equation in New Mexico to cumulative growing degree days (CGDD) crop coefficients (Sammis et al., 1985). This study concluded that these curves were adaptable to anywhere in New Mexico but use beyond the state would have to be further researched. Stegman (1988) studied the adaptability of regionally developed corn crop curves, used with the Jensen-Haise or modified Penman equations, to other areas in the Central United States. He then proposed a series of mean crop curves that were functions of the relative growing degree days from crop emergence to physiological maturity.

Steele et al. (1995) introduced fifth order polynomial mean crop curves for both the Jensen-Haise and Penman-Allen (1986) ET_r equations as functions of both DPP and CGDD since planting. When compared to eleven years of data from non-weighing lysimeters, it was determined that crop curves based on DPP were more accurate than those based on CGDD. A similar study, comparing time based and CGDD based crop curves, was conducted in Colorado with the researchers forming the opposite conclusion and preferring the CGDD method over DPP (Nielsen and Hinkle, 1995). This study was conducted for two years instead of eleven, however.

The ability to adapt K_c curves, based on a fraction of thermal units, to corn cultivars that require varying thermal unit totals from planting to physiological maturity was studied by Amos et al. (1989). In this study, they successfully derived a basal crop

coefficient curve from field data in Kansas which was able to be used for different cultivars.

The basal crop coefficient is often adjusted for effects of soil surface wetness, differences in soil drying properties, and available soil water. A dimensionless coefficient dependent on available soil water (K_a) was developed in Idaho by Jensen et al. (1970). A variation of the same coefficient was derived from field measurements in Colorado (Boonyatharokol and Walker, 1979). Another coefficient, K_s , adjusts for increased evaporation from a wet soil following a rainfall or irrigation event (Jensen et al., 1970, 1971).

2.3 Adoption of Irrigation Scheduling

The practice of scientific irrigation scheduling (SIS) has been proven in many studies to save the producer water and pumping energy and increase yields (Field et al., 1988, Steele et al., 1994, Buchleiter and Heerman, 1986, Shae et al. 1999, Heinemann et al., 2000, Steele et al., 2000). In the Steele et al. study in 2000, they were able to save 30% in irrigation inputs (water and energy) along with increasing yield 5% using scientific scheduling compared with grower practices. Melvin and Payero (2003) conducted a study of irrigation strategies for corn. They found by eliminating early season irrigation, unless a drought was occurring, and maintaining soil moisture at adequate levels thereafter, they could achieve 97% of the yield while only using 69% of the water compared to a farmer not practicing SIS.

Although the benefits of SIS have been proven, the adoption of the technique by growers has been slow. A study by Carlson (1975) of Southeastern Idaho irrigators found that less than 25% were utilizing SIS. Shearer and Vomocil (1981) determined that the adoption of SIS was well accepted by growers but it was not practiced when technical support was removed. Lieb et al. (2002) found that as few as 18% of producers in Washington state used SIS once technical support was no longer in place. In a paper by Clyma (1996), he stated that he believes the practice of SIS is actually decreasing.

The reasons for the poor rate of adoption of SIS by growers have been discussed by many authors. Carlson (1975) found that the pattern of farm practices and the social structure surrounding the farm were the most important factors to consider in the adoption of SIS. He also presented a series of five stages the grower will go through during the process of accepting a new technique. Itier (1996) believed that SIS techniques must match the training level, time limitations, and income potential of the growers. The view of Clyma (1996) was that growers need simpler, more comprehensive support for adoption to occur.

A study by Bauder (2005) of Eastern Colorado irrigators, found that using weather station ET was practiced as a secondary method of scheduling irrigations behind the farmers using their past experience. The study also concluded that only 7 to 9% of the growers surveyed actually knew the crop water use of their irrigated fields in 2001. Howell (1996) concluded that there has been little change in the theory behind SIS in the last 25 years, but there has been significant improvements in information technology that need to be applied to the field in order for adoption to occur.

2.4 Existing Technology

The concept of scheduling irrigation timing and application depth with computers has been around for many years. Frietag and Stegman (1982) developed a microcomputer based system for a center pivot in North Dakota. Daily values of solar radiation and temperature were collected from in-field sensors and input into the Jensen-Haise ET equation to determine soil moisture deficits. In-field precipitation amounts were also taken and irrigation amounts were manually entered to adjust the soil moisture balance. An irrigation cycle was initiated when the soil moisture deficit exceeded a predetermined level.

Homan et al. (1987) introduced a microcomputer based system that used climatic data and plant growth models to develop water schedules for center pivot irrigation. The irrigator was able to start and stop the pivot manually or by programming the microcomputer to start and stop at given times. There was also an alarm system that alerted the grower if the pivot malfunctioned or if power was interrupted.

Thomson et al. (1980,1982) developed and tested a microprocessor based irrigation controller for a small center pivot at the University of Georgia. The irrigation decision was based on four tensiometer stations located in two quadrants of the field.

A microcomputer based program was also used to implement the water balance method on a center pivot at North Dakota State University (Wagner et al., 1985). Daily ET estimates were made with the Jensen-Haise equation and then multiplied by crop coefficients developed specifically for North Dakota conditions (Stegman et al., 1977).

The system allowed growers to manually update parameters. It also alerted the user of equipment malfunctions and allowed for remote stop, start, and speed control.

There are also various software programs currently available that allow growers to implement SIS. A comprehensive review of these programs was completed by Henggeler (2002).

2.5 Review of Methods of Irrigation Scheduling

There are many methods currently available that can be used for irrigation scheduling and there are numerous studies comparing these methods. Stegman (1986) compared using allowable root zone water depletions, leaf water potentials, crop water stress indices, and ET replacement fractions to determine irrigation timing. A study in South Carolina was conducted to compare using water balance, tensiometers, or evaporation pans to schedule irrigations for corn and soybeans in the region (Camp et al., 1988). Steele et al. (1994) compared using partial ET replacement, measured soil matric potential, crop water stress index, and CERES-Maize growth model estimates to an allowable root zone depletion method. This study determined that the best yield per unit ET was attained by triggering irrigations when the soil water tension at the 0.3 m depth was greater than 50 kPa.

Some researchers have looked at the concept of scheduling irrigation timing and depth based on an economic analysis. A cost/loss risk analysis for scheduling irrigation was proposed by Rogers and Elliot (1988) for grain sorghum. This system decreased water application as the cost to irrigate increased or crop values decreased. This

scheduling method was determined by the researchers to have lower returns than stage of growth schedules, although it was not statistically evident. Dynamic programming was used by Loftis (1981) to schedule irrigations. The timing and amount of irrigation was determined using the relationship between soil moisture and crop yield.

The use of telemetry in monitoring and controlling irrigation has been around for many years. Duke et al. (1983) used two-way radio technology along with a host microcomputer to control up to 15 center pivots. Pogue (1987) implemented a commercial stand alone remote soil moisture sensing system distributed by the Irrrometer Company. The system required burying long lengths of cable into the field to connect sensors to a centralized data collection unit. Thompson and Threadgill (1987) sensed soil moisture and transmitted the data through cables to a centralized microcomputer data acquisition system for irrigation scheduling of a center pivot. An infrared telemetry based system was proposed by Ahmed and Al-Amoud (1993) to perform automatic irrigation scheduling based on soil moisture. This system offered a lower cost and much less labor intensive means of installation for monitoring weather and soil moisture data compared to its predecessors. It did, however, require line-of-site and was susceptible to malfunction during certain atmospheric conditions, i.e. fog, sunrise, and sunset.

The need to determine accurate, real-time measurements of pivot status has been recognized. Thomson and Smith (1992) stated that the pivot speed may vary up to 30% from what is expected. This error may result in incorrect water and chemical application depths. To remedy this problem, they developed a mechanical system that can be

interfaced to an onsite computer to help in determining center pivot position in the field and also its rotational speed.

2.6 Soil Moisture

Basing the irrigation decision solely on soil moisture measurements has been practiced by growers for years and also debated by researchers. More recently, Schmitz and Sourell (2000) attempted to quantify the measurement uncertainty of some commercially available granular matrix, electro conductivity, and time-domain reflectometry sensors. The researchers concluded due to the large amount of scattering that occurred over time that scheduling irrigations with these three instruments should not be done without first considering the high amount of uncertainty associated with their measurements. A study conducted in Colorado implemented over 8,500 acres of irrigated fields with neutron probe access tubes, tensiometers, electrical resistance blocks, and continuously recording data loggers with visual displays (Sanden et al., 2003). They determined that soil and crop rooting variability make it nearly impossible to precisely calibrate the moisture sensors and that using absolute numeric thresholds output by these sensors had its limitations. They recommended a system that continuously displays the relative changes in soil moisture. The same general recommendation was given by Melvin and Payero (2003).

Another approach to estimating the soil moisture content in a field is by using an ET equation that is adjusted periodically by soil moisture sensors. Steele et al. (1997) attempted to determine the frequency in which the field soil moisture balance that is

calculated using ET estimates should be corrected with soil moisture measuring devices. They found that corrections should be made at least monthly and preferably semi-monthly.

2.7 Impact of Water Stress

The effect of moisture stress on corn crop yield appears to vary throughout the growing season. It has been found by various researchers that corn yields are not very sensitive to moisture stress before tasseling and after dough stage, but are extremely susceptible to yield reductions from silking to blister stages. Gilley et al. (1980) performed some field tests on a corn crop in Nebraska in which they withheld irrigation during the vegetative stage of growth and then fully watered the field for the rest of the season. They determined that there was a water savings of over 4 inches or 30% with no reduction in yield. A similar management technique was employed by Melvin and Payero (2003) in their “Water Miser BMP” irrigation strategy. The only difference is that they initiated irrigation if the soil water depletion exceeded 70% during the vegetative stage. These researchers also presented a case for only allowing 40% soil moisture depletion during the critical growth stages instead of the traditional 50%.

2.8 Yield Models

Many equations have been developed that attempt to estimate yield based on moisture stresses. These equations are a valuable tool for determining the effectiveness

of an irrigation management strategy when actual yield data is not available or the crop growing season is being modeled.

A yield model which estimates the ratio of actual yield to maximum potential yield possible under the given conditions was derived by Stewart et al. (1977). They developed a ratio that is dependant upon the ratio of potential ET to maximum crop ET and a calibration constant, which varies with the susceptibility of the crop to water stress. Stegman (1982) estimated yield reductions for corn in North Dakota based on ET deficits during the vegetative, reproductive, and grain fill growth stages. Von Bernuth et al. (1984) developed a linear relationship between relative yield and the ratio of actual to potential seasonal transpiration. Stone et al. (1995) developed a yield model adaptable to many different crops. This model uses crop susceptibility weighting factors dependent on specific growth stages of the crop's development to determine a specific yield.

CHAPTER III

MATERIALS AND METHODS

Irrigation scheduling simulator software, which calculated soil water balances and determined irrigation timing and depth of application for each six degree section on a full circle (360 degree) center pivot, was written in *LabView™ Version 7.1*. The software simulated an entire growing season of a selected crop. The original software routine was developed for corn and was later adapted for use with soybeans and potatoes. The simulations were run for a typical center pivot irrigating one crop planted on one soil type. Table 3.1 specifies parameters that were held constant for all simulations:

Table 3.1: Simulation constants

Constant	Value
System Length	418 m
Initial Soil Water Balance	80% of Field Capacity
System Application Efficiency	90%
Pivot Starting Point	0° (North)
Section Being Analyzed	175-180° From North
Time To Complete One Revolution @ Max Speed	12 hrs

Simulations were conducted for all years with available weather data, at all sites, and for all three crops, three different pumping rates (37.9, 50.5, and 63.1 L/s), and available soil water holding capacities (83, 125, and 167 mm/m). The treatments simulated each year are listed in Table 3.2.

Table 3.2: Treatments administered at all sites for all years with available weather data.

Treatment	Soil WHC (mm/m)	System Pumping Rate (L/s)
1	83	37.9
2	83	50.5
3	83	63.1
4	125	37.9
5	125	50.5
6	125	63.1
7	167	37.9
8	167	50.5
9	167	63.1

The following daily values were output into a *Microsoft Excel™* file by the *LabView* software for analysis: date, K_c , ET, rainfall, irrigation depth applied, irrigator position, actual water balance, minimum allowable balance, field capacity, days under minimum allowable, and weather values.

3.1 ET Estimation

Scientific irrigation scheduling relies on the ability to accurately estimate evapotranspiration (ET). The ASCE Penman Monteith (Allen et al., 2005) alfalfa reference equation was chosen as the primary method of determining daily ET (Equation 3.1). This equation requires daily weather values of maximum and minimum temperature, average wind speed, average relative humidity, and total solar radiation. This method was selected because of its overall reliability, acceptance by the scientific

community, and the ability to transfer crop coefficients to other alfalfa referenced ET equations.

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{1600}{T + 273} \mu_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.38\mu_2)} \quad (3.1)$$

where,

ET_r - reference evapotranspiration [mm d^{-1}],

R_n - net radiation at the crop surface [MJ m^{-2}],

G - soil heat flux density [MJ m^{-2}],

T - mean daily air temperature at 2 m height [$^{\circ}\text{C}$],

u_2 - wind speed at 2 m height [m s^{-1}],

e_s - saturation vapor pressure [kPa],

e_a - actual vapor pressure [kPa],

$e_s - e_a$ - vapor pressure deficit [kPa],

Δ - slope vapor pressure curve [$\text{kPa } ^{\circ}\text{C}^{-1}$],

γ - psychrometric constant [$\text{kPa } ^{\circ}\text{C}^{-1}$]

Simulations were also conducted at selected sites using the Jensen-Haise equation to estimate ET. Equation 3.2 (Jensen and Haise, 1963) is an alternative to the ASCE PM and only requires daily inputs of solar radiation along with maximum and minimum temperatures. Eliminating the need for wind speed and humidity measurements may be advantageous because the sensors themselves are much less reliable than sensors for solar

radiation and temperature. It also could reduce costs and allow the weather monitoring system to be more economical to the farmer.

$$ET_r = 0.0102(T_m + 3.36)R_s \quad (3.2)$$

where,

ET_r – reference evapotranspiration (mm d⁻¹)

T_m – average daily temperature (°C)

R_s – solar radiation (MJ m⁻²)

3.2 Reference ET Coefficients

ET_r for both ET estimation methods was multiplied by a crop specific crop coefficient (K_c) and also a plant available water coefficient (K_a) (Equation 3.3).

$$ET_c = ET_r * K_c * K_a \quad (3.3)$$

where,

Et_c – estimated crop evapotranspiration (mm)

ET_r – reference evapotranspiration (mm)

K_c – crop coefficient

K_a – plant available water coefficient

Crop coefficients were developed specifically for this study (Figure 3.1). The coefficients were adapted from methods presented in the FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998) and values listed in the ASCE Standardized Reference

Evapotranspiration Equation (Allen et al., 2005). FAO 56 was used as a basis for determining the length of specific growth stages. Length of the individual stages and total growing period for specific climates, locations, and for a wide variety of crops are provided in the paper along with a method for setting up a crop coefficient curve.

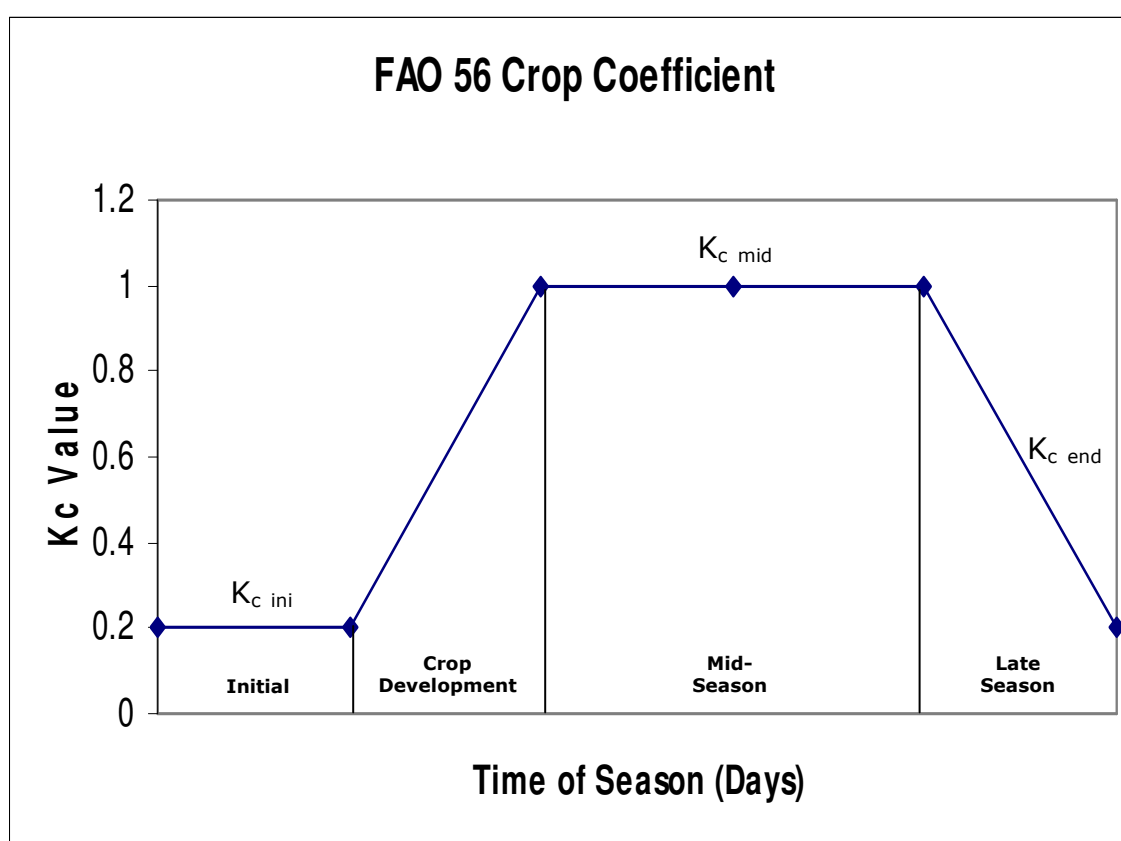


Figure 3.1: Form of crop coefficient curve used in the FAO 56 method.

Since values for the upper Great Plains are not specifically mentioned, the length of the specific growth stages for this region were derived by taking the average percentage of the total growing season that was needed to complete an individual growth

stage from the climates presented. Table 3.3 displays the percentage of the crop maturity that was derived for each crop to reach the end of a specific growth stage.

Table 3.3: Derived values for the percentage of crop maturity needed to complete the specific growth stages used to determine crop coefficients.

Crop Type	Initial	Crop Development	Mid-Season	Late Season
Corn	18%	48%	76%	100%
Potatoes	21%	44%	80%	100%
Soybeans	15%	40%	80%	100%

The actual values for the K_c were taken from those recommended by Allen et al. (2005) to be used with the ASCE PM equation. The K_c values for the initial, mid-season, and late season growth stages are displayed in Table 3.4.

Table 3.4: Seasonal K_c values.

Crop Type	K_c ini	K_c mid	K_c late
Corn	0.2	1	0.2
Potatoes	0.2	0.8	0.2
Soybeans	0.2	1	0.1

Figure 3.2 is a graphical representation of the crop coefficient for the three crops as the crop progresses from planting to full physiological maturity. In their initial stage of development, all of the crops modeled use 20% of the water compared to the alfalfa reference crop. Corn and soybean crops use the same amount of water as the referenced alfalfa in mid-season while potatoes use only 80% of the water. The soybean crop, compared to corn and potatoes, spends the greatest percentage of time in the mid-season or high water use stage (from 40-80% of physiological maturity).

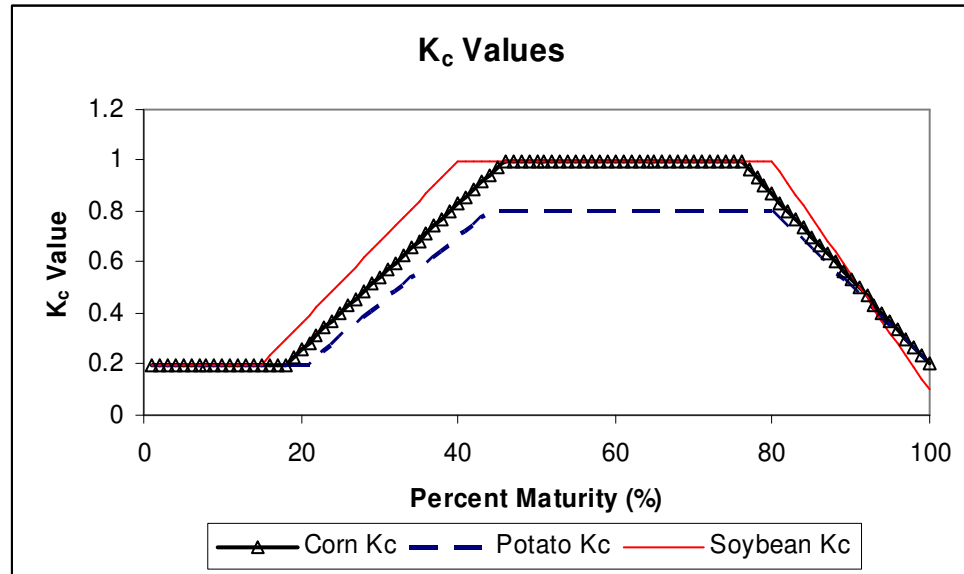


Figure 3.2: Graphical representation of K_c values for corn, soybeans, and potatoes.

The ET_r values were also multiplied by a plant available water coefficient (K_a) derived by Jensen et al. (1990) (Equation 3.4).

$$K_a = \frac{\ln(AW + 1)}{\ln(101)} \quad (3.4)$$

where,

K_a – plant available water coefficient

AW – available water (%)

The two reference ET equations used in this study were derived with the assumption that soil water is not limiting. This coefficient takes into effect the resistance of the transfer of water into the atmosphere as soil moisture is depleted. As the available soil water is depleted, the water left within the pore space becomes bound more tightly to

the soil particles. Therefore, as the percentage of soil water decreases, so does the value of the coefficient as illustrated in Figure 3.3.

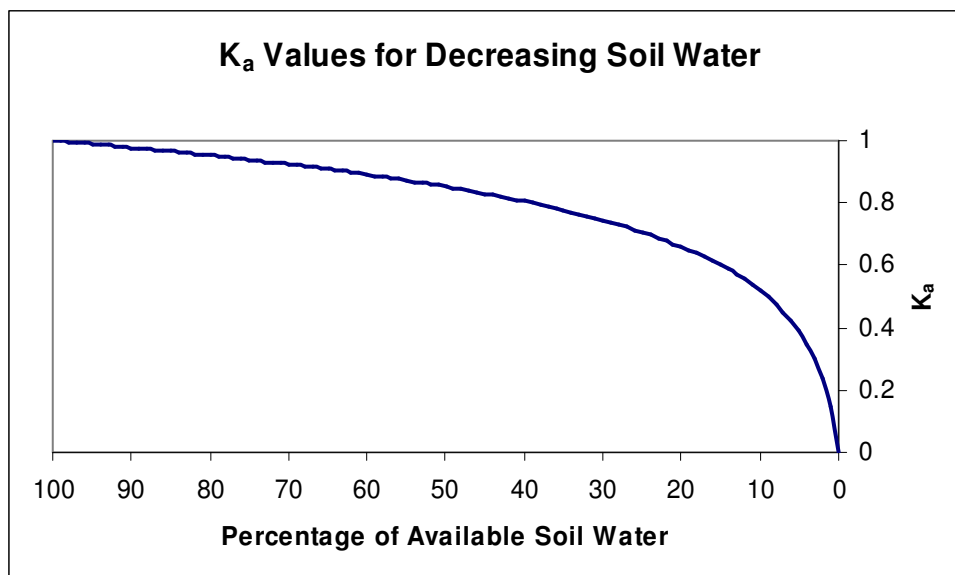


Figure 3.3: K_a values as percentage of available soil water decreases from left to right.

3.3 Simulation Data Sets

Simulations were conducted using weather data, when available, for the last twenty years (1986-2005) from Akron, CO, Ames, IA, Brookings, SD, Oakes, ND, Ord, NE, Rock Port, MO, and St. John, KS. Required daily weather data and rainfall totals were downloaded from the High Plains Regional Climate Center (2005) online databases for each of the simulated sites and years. The Rockport, MO site only had data available from 1991-2005 and the Oakes, ND site had data available from 1990-2005. These data were then transferred into text files that could be read by the simulation software.

3.4 Growing Season Lengths

The reference evapotranspiration (ET_r) value was calculated for each day past a specified planting date. The planting dates along with an assigned season length for corn are shown in Table 3.5. The planting dates are based on regional averages for the given site and season lengths are the approximate number of days from planting date to the 30th of September.

Table 3.5: Corn planting dates and season lengths for the seven locations.

Site	Planting Date	Season Length (Days)
Akron, CO	April 1	180
Ames, IA	April 1	180
Brookings, SD	April 15	165
Oakes, ND	May 1	150
Ord, NE	April 1	180
Rockport, MO	April 1	180
St. John, KS	April 1	180

Planting dates for soybeans and potatoes were also based on regional averages with the season lengths being determined from the approximate number of days from planting to the 15th of September (Table 3.6).

Table 3.6: Soybean and potato planting dates and season lengths

Site	Soybeans Planting Date	Soybeans Season Length (Days)	Potatoes Planting Date	Potatoes Season Length (Days)
Akron, CO	May 1	135	April 1	165
Ames, IA	May 1	135	April 1	165
Brookings, SD	May 15	120	April 15	150
Oakes, ND	June 1	100	May 1	135
Ord, NE	May 1	135	April 1	165
Rock Port, MO	May 1	135	April 1	165
St. John, KS	May 1	135	April 1	165

3.5 Crop Rooting Depth

Rooting depth for the three crops simulated was initially set to 0.3 m to provide a buffer at the beginning of the season and was assumed to increase linearly to a maximum effective depth when the crop reached its maximum height above the soil surface. The maximum height was assumed to be reached when the crop coefficient initially reached its maximum value. Both corn and soybeans were assumed to have a maximum effective rooting depth of 0.9 m while the effective depth for potatoes was set to 0.6 m. Effective rooting depth is the depth managed for irrigation, not necessarily the total rooting depth.

Figure 3.4 shows how rooting depth was determined for corn. When corn is planted, or at zero percent maturity, it has an actual rooting depth of zero. To give the soil some water holding capacity and eliminate the need for frequent early season irrigation amounts, the initial effective rooting depth (what the software sees as actual rooting depth) was set to 0.3 m. The actual rooting depth was then increased linearly from 0% maturity to 48% maturity, which is when the crop coefficient initially reaches

its maximum value and the maximum rooting depth of 0.9 m is achieved. When the actual rooting depth becomes equal to or greater than 0.3 m (at approximately 16% maturity), the actual rooting depth and effective rooting depth become equal and remain this way for the rest of the growing season. The same method was used to determine the effective rooting depth for both potatoes and soybeans. The actual and effective rooting depth became equal at 13% maturity for soybeans and at 22% maturity for potatoes.

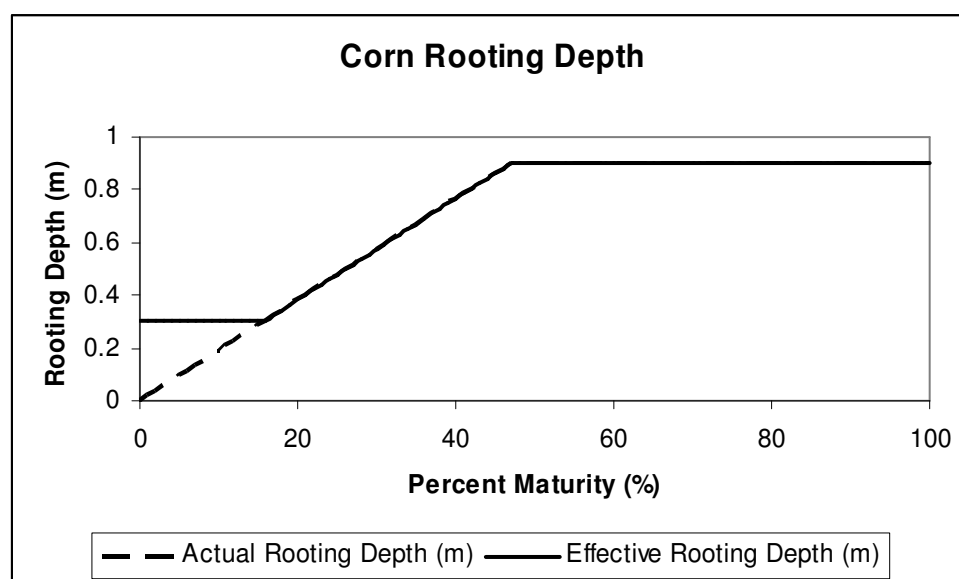


Figure 3.4: Actual and effective rooting depth for corn.

3.6 Allowable Soil Water Balance

The minimum allowable soil water balance was set to a level that would not limit the crop development and yield potential. The goal of the software was to maintain the soil water balance in all parts of the field between the minimum allowable amount and field capacity. Similar to the formation of the K_c curve, each crop's growing season was

divided into four stages; initial, developmental, mid-season, and late season. Crops entered and exited stages based on their percentage of total maturity (Table 3.7).

Table 3.7: Percentage of crop maturity needed to complete crop growth stages.

Crop Type	Initial	Crop Development	Mid-Season	Late Season
Corn	30%	50%	70%	80%
Potatoes	25%	40%	85%	90%
Soybeans	40%	60%	85%	90%

During the initial and late season stages, soil water levels were allowed to drop further below field capacity than in mid-season, which is when the critical stage of crop development occurs for corn, potatoes, and soybeans. The developmental and late season stages were used as transitions to raise and lower the minimum allowable percentages of field capacity to meet the crop's water demands. Initial growth stage minimum allowable soil water levels were set at 30% of field capacity for corn and soybeans and 40% for potatoes. During the critical mid-season stage, the irrigation scheduling software attempted to maintain the minimum allowable balance above 70% of field capacity for potatoes followed by corn at 60% and soybeans at 50% of field capacity. After the late season phase, soil water levels were allowed to drop to 40% for potatoes, 30% for corn, and 20% for soybeans.

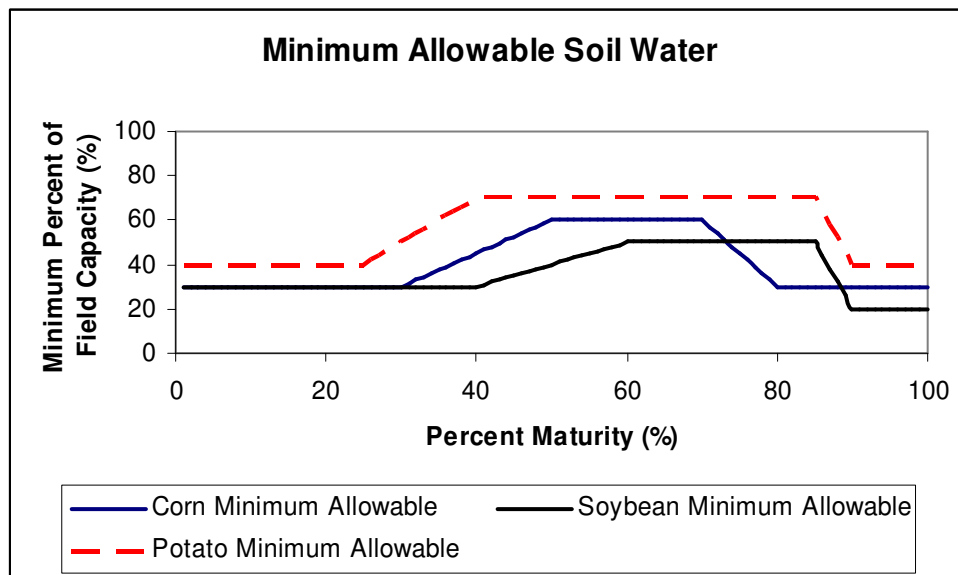


Figure 3.5: Minimum soil water levels allowed throughout the irrigation season for corn, potatoes, and soybeans.

As can be seen in Figure 3.5, potatoes are more sensitive to depleted water levels throughout their growing season than corn and soybeans. It should be noted that these minimum allowable soil water levels are conservative estimates of the water level depletions that may result in stress and yield reductions in the crops.

3.7 Irrigation Depth

A maximum irrigation application depth was set to provide a buffer which would allow for a rainfall event after an irrigation that would not exceed field capacity. The percent maturity needed to reach the end of a specific growth stage was identical to that used to determine minimum allowable soil water levels. The maximum application depth value was set to 60% of field capacity in the initial growing stage for corn, soybeans, and potatoes. During the mid-season growth stage, both corn and potatoes were allowed to be

irrigated to 80% of field capacity while soybeans were held to 70% of field capacity. After the late season growth stage, corn and potatoes could be irrigated up to 50% and soybeans up to 40% of field capacity. The maximum depth of water that could be applied at one time was set at 32 mm with a minimum depth of 13 mm.

Figure 3.6 shows the changing minimum allowable and maximum application limits for corn as it progresses through the growing season. Early and late in the season, as mentioned above, the maximum application limit was set to a lower percentage of field capacity to allow for rainfall events common to this time period in the upper Great Plains. During the mid-season growth stage, the maximum application limit is increased to 80% of field capacity to allow for room between the minimum allowable and field capacity and also because this period typically has less rainfall.

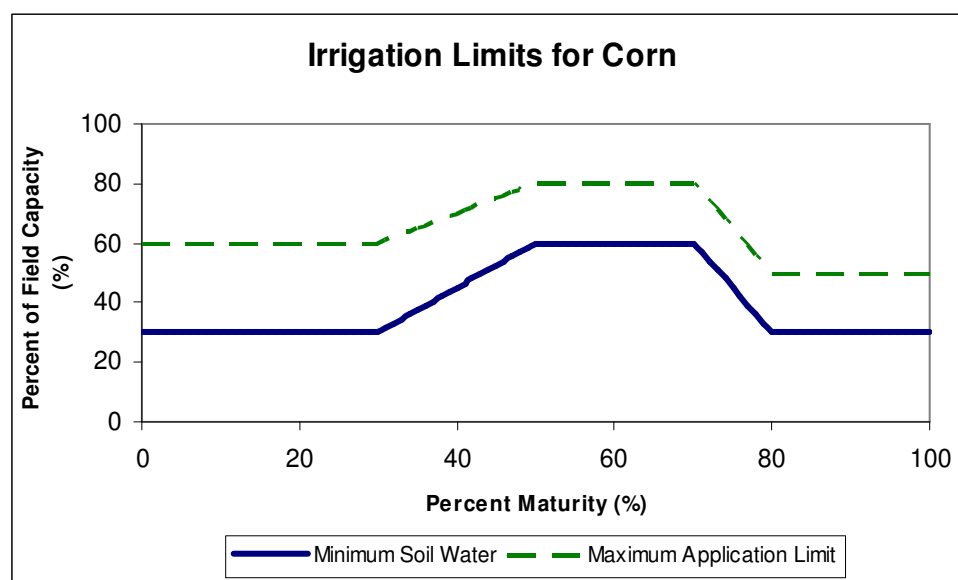


Figure 3.6: Maximum application depth as corn progresses through the growing season.

3.8 ET Forecasting

ET forecasting was used to plan the timing and depth of irrigation applications. For corn and soybeans, the predicted four day future ET total was found by taking the average of the previous four day's ET and projecting it onto the next four days. With potatoes, the average of the previous four day's ET was used to determine the ET total for the next three days. Using the previous four day's ET average was chosen over using the previous two day, three day, and historical averages because it deviated the least from the actual seasonal ET total that occurred.

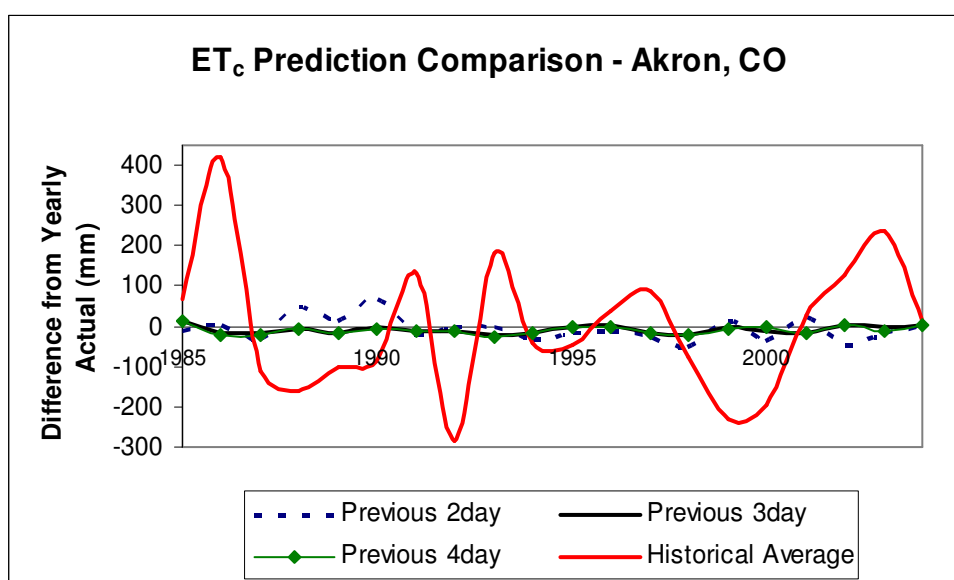


Figure 3.7: Deviation from the yearly actual ET using the previous two day, three day, four day, or historical average estimate at Akron, CO.

The difference in the number of days the average four day ET is projected onto was due to the fact that normally smaller irrigation amounts are applied more frequently to potatoes compared to corn and soybeans. Since there are smaller amounts added, the time it takes for the pivot to complete one revolution is decreased. In the worst case

scenario, a 418 m long pivot may need to replenish up to four days of ET depletions for corn and soybeans compared to three days for potatoes.

The predicted four or three day ET total was then subtracted from the current soil water balance for each six degree segment of the pivot. If this predicted balance fell below the minimum allowable soil water balance, that individual section of the field was determined to be in need of irrigation within the next three or four days depending on the crop type. The application depth was then determined for each section by subtracting the predicted balance from the maximum application depth. Provided that this depth was between the allowable limits, the center pivot was operated to apply the specified amount to each section.

3.9 Rainfall

Daily rainfall was added to the soil water balance. All rainfall amounts at each location were considered effective; but if the soil water balance for any one day exceeded the field capacity due to rainfall, irrigation, or a combination of the two, the balance was held at field capacity for the following day. The only exception to this rule was when the ET for the following day was greater than the excess amount above field capacity. In this case, the soil moisture balance was found by subtracting the ET from the sum of field capacity and excess. All excesses were considered to be lost to runoff or deep percolation.

3.10 Relative Crop Yield

To analyze the effectiveness of the simulation software along with determining the accuracy of the minimum allowable depletions set for corn, a yield model was chosen (Shaw, 1978).

$$YR_d = 100 - 1.22SDI_d \quad (3.5)$$

where,

YR_d - relative yield from drought stress as a percent

SDI_d - stress day index for drought conditions

The stress day index is defined on a cumulative basis by:

$$SDI_d = \sum_{j=1}^N SD_{dj} \times CS_{dj} \quad (3.6)$$

where,

SDI_d - stress day index for drought conditions for N number of growth periods (5 day long) in the growing season

SD_{dj} - stress-day factor for drought conditions for growth period j

CS_{dj} - crop susceptibility factors for growth period j

The stress day factor is determined by inserting the ratio between the actual ET to the potential ET into Equation 3.7. The potential evapotranspiration (ET_p) is found by multiplying the ET_r by the crop coefficient while the ET_a is found by multiplying the ET_p by the plant available water coefficient. The only variable in the stress day factor formula is the percentage of available water in the soil. As the percentage of available

water decreases, the ratio of actual to potential ET decreases which increases the stress day factor.

$$SD_{dj} = \sum_{k=1}^{nj} (1.0 - ET_a / ET_p) \quad (3.7)$$

where,

SD_{dj} = stress-day factor for drought conditions in the nj days in the j th growing period,

ET_a = actual daily ET (mm/d)

ET_p = potential daily ET (mm/d)

The crop susceptibility factors (Table 3.8) range from 0.5 during less critical stages of corn crop development to 2.0 during the tasseling stage, which is the period that the crop is most susceptible to moisture stress.

Table 3.8: Crop susceptibility factors.

Period	Date	CS _a	Period	Date	CS _a
-8	Tasseling (-) 35 days	0.5	1	Tasseling (+) 5 days	2
-7	Tasseling (-) 30 days	0.5	2	Tasseling (+) 10 days	1.3
-6	Tasseling (-) 25 days	1	3	Tasseling (+) 15 Days	1.3
-5	Tasseling (-) 20 days	1	4	Tasseling (+) 20 Days	1.3
-4	Tasseling (-) 15 days	1	5	Tasseling (+) 25 Days	1.3
-3	Tasseling (-) 10 days	1	6	Tasseling (+) 30 Days	1.3
-2	Tasseling (-) 5 days	1.75	7	Tasseling (+) 35 Days	1.2
-1	Tasseling	2	8	Tasseling (+) 40 Days	1
			9	Tasseling (+) 45 Days	0.5

The tasseling stage used in the yield model was determined at each site for every year that a simulation was completed. The corn crop was found to reach tasseling after a

predetermined number of GDD had been accumulated (Table 3.9). GDD were calculated based on the 86/50 scale for maximum and minimum temperatures.

Table 3.9: Accumulated GDD to tasseling.

Site	GDD to Tasseling
Akron, CO	1450
Ames, IA	1450
Brookings, SD	1200
Oakes, ND	1130
Ord, NE	1450
Rock Port, MO	1450
St. John, KS	1450

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Corn Simulations Using ASCE Penman Evapotranspiration

4.10 Akron, CO

Table 4.1: Akron, CO ASCE PM corn simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM*	Irrigation Events	Irrigation Depth (mm)	Relative Yield
1	748	338	526	41	19	27	77
2	817	338	609	21	23	27	88
3	855	338	630	16	23	27	90
4	753	338	509	41	17	30	78
5	812	338	574	20	19	30	88
6	842	338	617	5	21	30	93
7	749	338	495	44	16	31	77
8	802	338	551	23	18	32	87
9	830	338	582	6	19	31	91

* Days below minimum soil water balance

The planting date for corn at Akron, CO was simulated to be April 1 with the crop reaching full maturity on September 30. This site averaged the least amount of rain of all the sites used for simulations in this study at 2 mm/d or 338 mm/growing season with a standard deviation 162 mm/growing season. The growing season with the least amount of rainfall occurred in 1994 when only 175 mm of rainfall was recorded. The largest rainfall total from April 1 through September 30 occurred in 1996 when 759 mm of rain fell. Figure 4.1 shows growing season rainfall for the study period.

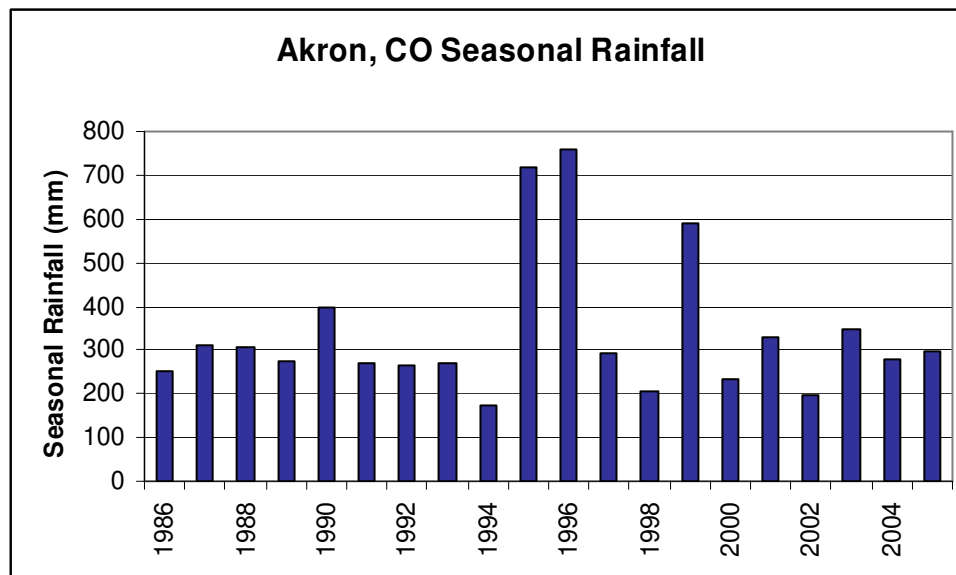


Figure 4.1: Seasonal rainfall totals accumulated during the corn growing season at Akron, CO.

A 37.9 L/s system is unable to meet the ET demands of this geographic region for a corn crop on a soil with a water holding capacity (WHC) of 83 mm/m. The simulator produced three indicators. First, the average days below the minimum allowable balance (DBM) over the twenty years simulated was estimated at 41 for a 37.9 L/s system, 21 for the 50.5 L/s system, and 16 for a 63.1 L/s system. Second, the twenty year average seasonal ET_c for the 50.5 L/s system was 110% of the 37.9 L/s system while the 63.1 L/s system averaged 114% of the 37.9 L/s average. The value of ET_c is determined by multiplying ET_r by a crop coefficient and a plant available water coefficient. Since the crop coefficient was held constant for all the corn simulations at this site, the only variable is the plant available water coefficient. If the available soil water was below field capacity, the plant available water coefficient becomes less than one. This in turn causes the ET_c to become less and less as the available soil water depletes. The third

indicator is that when pumping rate is increased, the relative yield was found to respond significantly at the $p < 0.01$ level. The average relative yield increased from 77%, to 88%, to 90% for Treatments 1, 2, and 3 respectively (Figure 4.2).

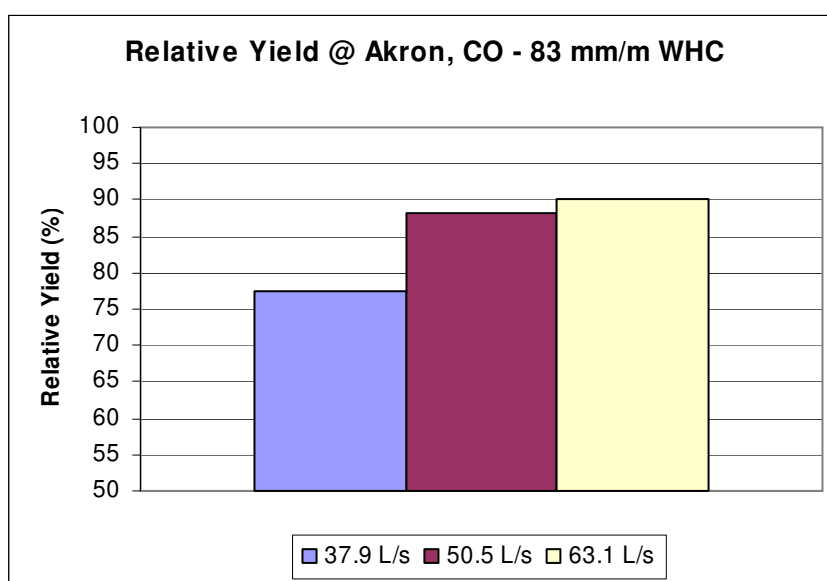


Figure 4.2: Average relative yield for all pumping rates simulated on a soil with a WHC of 83 mm/m at Akron, CO.

The average seasonal irrigation amount was 526 mm, 609 mm, and 630 mm for Treatments 1, 2, and 3 respectively. The average irrigation depth applied during each irrigation event was identical for each pumping rate simulated (27 mm). The increase in rotational speed of the pivot, allowed with a higher capacity system to apply the same volume of water, enabled the average number of rotations to increase from 19 for Treatment 1 to 23 with Treatment 2 to 24 with Treatment 3.

Increasing from 83 mm/m to 125 mm/m of soil WHC resulted in, for the most part, minimal changes in the twenty year averages. The most notable change was that the number of average DBM dropped from 16 to 5 for the 63.1 L/s system. The average

DBM for a 37.9 L/s system stayed constant at 41 and dropped from 21 to 20 for a 50.5 L/s system.

The average irrigation depth applied increased slightly when increasing the soil WHC from 83 (27 mm) to 125 (30 mm) mm/m of soil. However, the overall seasonal irrigation amount decreased with the coarser soil. The increase in soil WHC allows the excess rainfall, which pushes the soil water balance above field capacity in the lighter textured soil, to be stored in the root zone. Since this extra water is being stored in the soil, there is less need for irrigation. A perfect example of this occurred in 1996. That year had the highest seasonal rainfall total of 759 mm. The average amount of excess water lost to runoff or deep percolation dropped from 549 mm to 376 mm using Treatment 5 instead of Treatment 2.

Many of the same trends continued when going from the 125 mm/m to the 167 mm/m of WHC in the soil. The average DBM rose slightly along with the average irrigation depth applied for all pumping rates simulated while all other categories decreased slightly or underwent little change.

4.11 Ames, IA

Table 4.2: Ames, IA ASCE PM corn simulation averages.

Treatment	ET _c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Relative Yield
1	555	647	274	5	12	23	95
2	564	647	306	1	13	23	96
3	565	647	309	1	14	22	96
4	554	647	222	4	8	29	94
5	558	647	235	1	8	28	95
6	560	647	242	0	9	28	96
7	552	647	200	3	6	32	94
8	553	647	202	2	6	32	94
9	556	647	214	0	7	32	95

During the corn growing season at Ames, IA, the total seasonal rainfall averaged greater than the ET_c. The season at this site began with planting on April 1 and full maturity occurring on September 30. The average seasonal rainfall was 647 mm and average seasonal ET_c values ranged from 552 mm with Treatment 7 to 565 mm with Treatment 3. Despite this fact, irrigation was still needed at the site because the rainfall events often occurred during the initial and late season stages of the corn development. Seasonal irrigation amounts ranged from an average of 200 mm using Treatment 7 to an average of 309 mm with Treatment 3. Increasing pumping rate at this site was found to not significantly increase seasonal irrigation amounts at the p<0.01 level. However, increasing soil WHC did significantly decrease the amount of average seasonal irrigation applied at the p<0.01 level. DBM were held to a minimum at this site by the scheduling software. On the average, five DBM occurred with Treatment 1 while Treatments 6 and 9 resulted in no DBM. The number of rotations approximately doubled for each pumping

rate when the WHC was dropped from 167 mm/m to 83 mm/m of soil. Figure 4.3 shows the average number of irrigation events that occurred for each treatment.

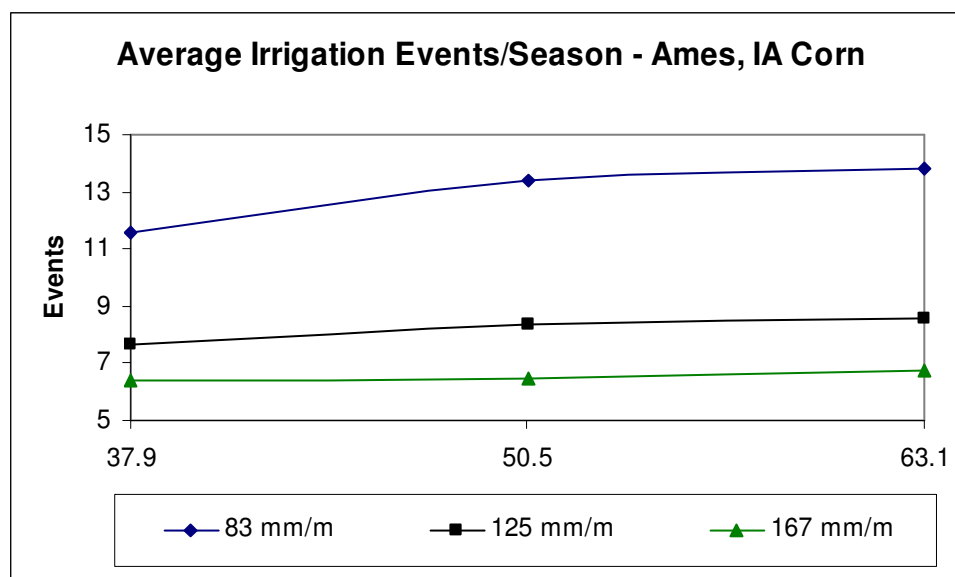


Figure 4.3: Average number of irrigation events simulated at Ames, IA on corn.

All system pumping rates simulated were able to keep up with the ET_c demand of this area. Relative yield values ranged from 94% for Treatments 4, 7, and 8 to 96% for Treatments 2, 3, and 6. Relative yield was found to significantly decrease with increased soil WHC and increase with increased pumping rate at the $p < 0.01$ level.

It may seem counterintuitive to see that the relative yield would decrease even though the soil WHC is increasing and DBM are decreasing. A closer look at the yield model used reveals that any actual soil water balance that is below field capacity causes the relative yield to be reduced. The amount of potential yield reduction is determined by the growth period relative to tasseling. The irrigation scheduling software does not attempt to maintain the soil water balance at field capacity, but instead tries to manage

between a minimum allowable soil water balance and field capacity. With the lower water holding capacity soil, the likelihood is greater that a rainfall event will meet or exceed field capacity. Hence, there may be more days when the water balance is at field capacity resulting in no calculated reduction in the relative yield. Comparing Treatment 5 to Treatment 8 for Ames in 2003 illustrates this point. The average relative yield dropped from 93% to 91% even though the DBM remained equal to one. When looking closer at the yield model, Treatment 5 had 11 days in which the water balance was equal to field capacity compared to eight days with Treatment 8. Since the days in which the actual balance was equal to field capacity all occurred during a period in which the crop susceptibility factor was equal for both treatments, Treatment 5 had a smaller yield reduction. The irrigation depth applied ranged from 22 mm with Treatment 3 to 32 mm for Treatments 7-9.

4.12 Brookings, SD

Table 4.3: Brookings, SD ASCE PM corn simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Relative Yield
1	514	431	293	5	12	24	94
2	521	431	324	1	14	24	96
3	525	431	327	1	14	23	96
4	510	431	263	5	9	29	93
5	516	431	264	1	9	29	94
6	518	431	275	0	10	29	95
7	504	431	236	6	8	31	91
8	510	431	243	2	8	32	93
9	512	431	247	0	8	32	93

The average seasonal rainfall at Brookings, SD was 431 mm for the 20 years simulated. The growing season for corn was simulated to begin on April 15 and end on September 30 each year. Average ET_c values for the 63.1 L/s pumping rates were approximately 102% of the 37.9 L/s systems and between 100 and 101 % of the 50.5 L/s systems.

The average DBM were greatest for Treatment 7 (6 days) and least for Treatments 6 and 9 (0 days). The average DBM actually increased from five (Treatments 1 and 4) to six days (Treatment 7). This seems counterintuitive because the soil WHC is actually increasing. This phenomenon can be attributed to the fact that when the soil WHC gets greater, a greater volume of water is needed to maintain the soil water balance above the minimum allowable balance. Since rainfall events are often less frequent during the time in which the minimum allowable balance and the ET demand are greatest, the soil water balance may need to be maintained by irrigation alone. An irrigation system that is only able to deliver 37.9 L/s may not be able to supply the volume of water needed in the time required, which in turn, increases the overall number of DBM. This situation occurred at the Brookings site in 2002. The seasonal rainfall total for this year was 407 mm, which is only 24 mm below the average. Figure 4.4 below shows that there was only 10 mm of rain from June 22 – July 27. The irrigation system at that time was applying the maximum amount of water in an attempt to keep up with the ET demand, but was unable to, which resulted in 23 DBM and a relative yield of 89%.

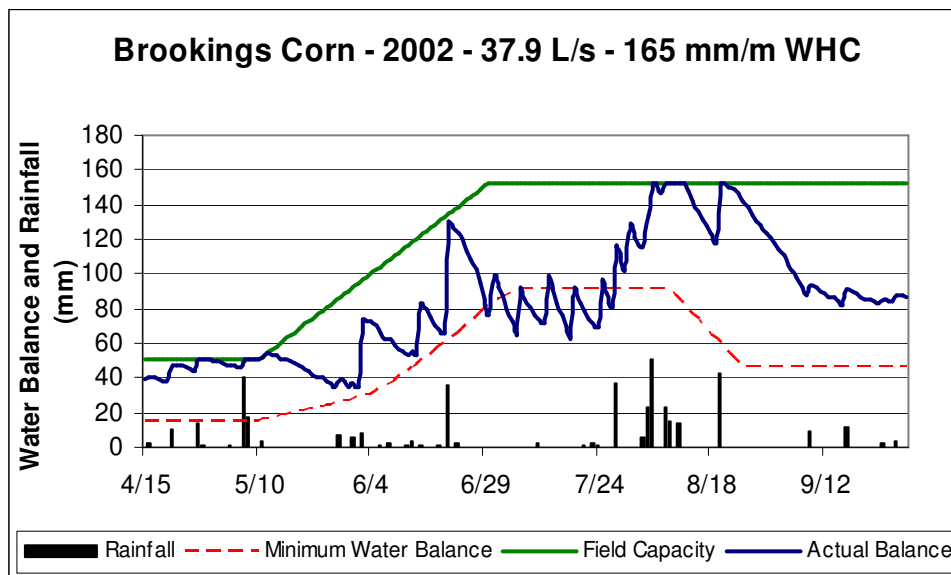


Figure 4.4: Field capacity, actual balance, minimum allowable balance, and rainfall events occurring using Treatment 7 for corn at Brookings, SD.

In comparison, a 63.1 L/s system under identical conditions was able to maintain the actual soil water balance above the minimum water balance (Figure 4.5). This pumping rate resulted in the zero DBM and a relative yield of 94%.

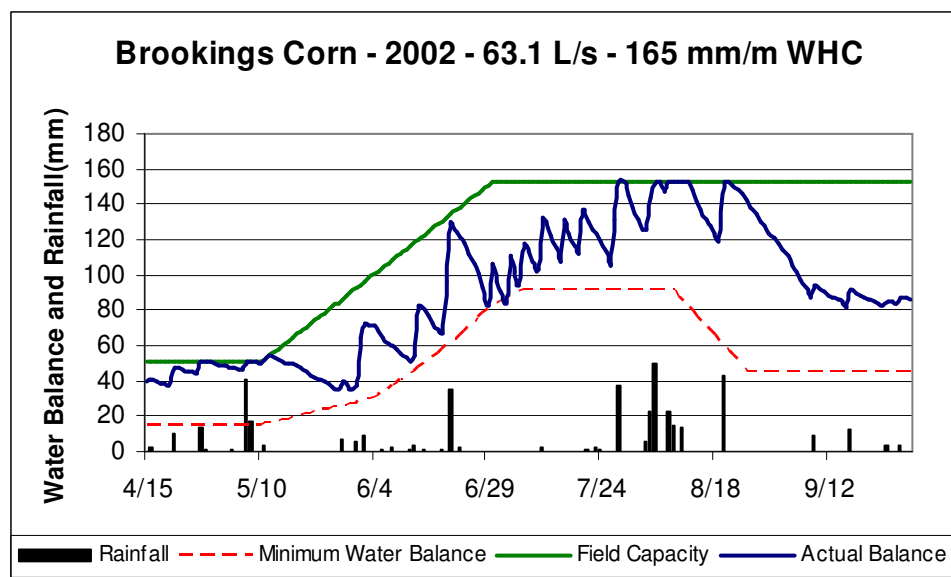


Figure 4.5: Field capacity, actual balance, minimum allowable balance, and rainfall events occurring using Treatment 9 for corn at Brookings, SD.

4.13 Oakes, ND

Table 4.4: Oakes, ND ASCE PM corn simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Relative Yield
1	459	363	264	3	11	24	94
2	465	363	279	1	12	23	96
3	466	363	283	1	13	22	96
4	454	363	230	3	8	29	93
5	458	363	240	0	9	28	94
6	460	363	246	0	9	28	95
7	449	363	219	4	7	33	91
8	452	363	218	1	7	32	92
9	453	363	218	0	7	31	93

The growing season for corn at Oakes, ND assumed planting on May 1 and physiological maturity on September 30. Weather data from the High Plains Regional

Climate Center was only available for this site from 1990-2005. The average seasonal rainfall was 363 mm with a standard deviation of 78 mm, which is the smallest standard deviation of the sites in this study, indicating the most consistent rainfall.

The number of DBM was held to a minimum at this site. The maximum number occurred with Treatment 7 (four days) and the minimum occurred with Treatments 5, 6, and 9 (zero days). The average seasonal irrigation amount significantly decreased with increased soil WHC while increasing the pumping rate had no significant effect at the $p=0.01$ level. The 167 mm/m of WHC soil had an average seasonal irrigation amount that was nearly identical for all pumping rates (219 mm for Treatment 7, 218 mm for Treatments 8 and 9).

The smallest seasonal irrigation depth applied to corn at Oakes was in 1993. For the pumping rates simulated on a soil with 167 mm/m of WHC only 32 mm of irrigation water was needed that year on either August 10 or 11. As shown in Figure 4.6, there were very few large rainfall events during the growing season, but many small amounts that were enough to meet the ET demand.

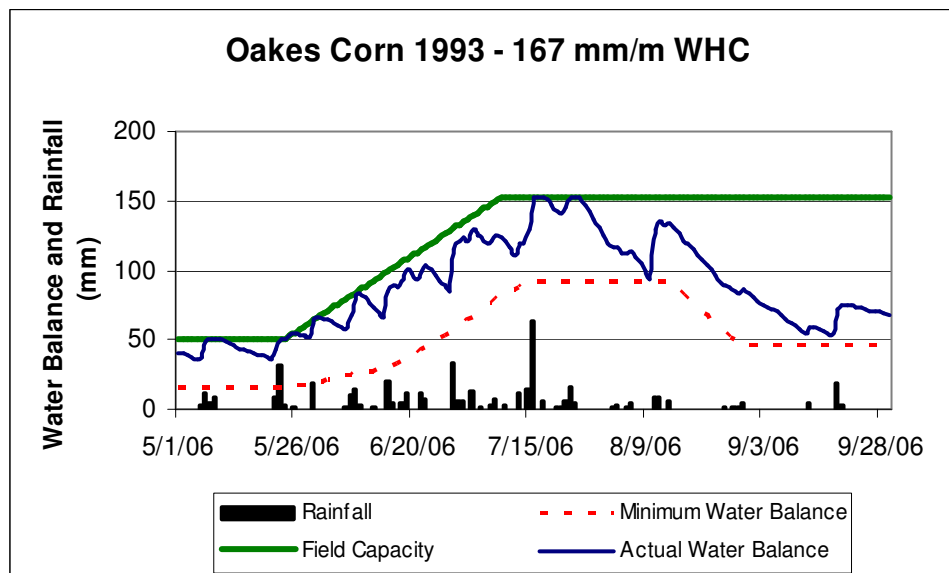


Figure 4.6: Tracking of actual water balance (blue line) for Treatments 7-9 during 1993 at Oakes, ND.

The number of rotations the irrigation system made over the growing season increased with the pumping rate for a given soil type while the depth of the irrigation applied generally decreased.

4.14 Ord, NE

Table 4.5: Ord, NE ASCE PM corn simulation averages.

Treatment	ET_c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Relative Yield
1	612	445	364	13	14	26	91
2	626	445	400	5	16	25	94
3	635	445	411	3	17	24	95
4	608	445	321	11	11	30	91
5	621	445	344	3	12	29	94
6	627	445	362	0	12	29	95
7	603	445	301	13	9	32	90
8	615	445	317	3	10	32	93
9	620	445	325	0	10	31	94

Average seasonal irrigation amounts at this site ranged from 301 mm for Treatment 7 to 411 mm for Treatment 3 while the average ET_c was greatest for Treatment 3 (635 mm) and least for Treatment 7 (603 mm). This relationship between Treatment 3 and 7 occurred at all the sites analyzed. The largest average irrigation and ET_c amounts occur with Treatment 3 because of the relatively low water holding capacity and the ability of the system to supply adequate amounts of water to keep the soil water balance above the minimum allowable. The WHC of the soil in Treatment 3 is one-third of Treatment 7, which causes some of the rainfall that is stored in the finer textured soil (Treatment 3) to be lost to runoff or deep percolation. This lost volume of water must be replenished by the irrigation system in order to maintain an adequate amount of water as to not induce moisture stress. Since a greater volume of water is being supplied to a coarser textured soil, the percentage of available soil water tends to be greater throughout

the growing season. This, in turn, keeps the value of the plant available water coefficient and ET_c higher using Treatment 3 compared to Treatment 7.

An example of this occurred in 1988. Rainfall for this growing season was 521 mm, which was 76 mm above the 20 year average. Seasonal ET_c amounts were 808 mm and 740 mm for Treatments 3 and 7, respectively. Seasonal irrigation totaled 630 mm for Treatment 3 and 445 mm for Treatment 7. Figure 4.7 tracks the percentage of available water throughout the growing season for the two treatments. It can be seen that Treatment 7 tends to have a higher percentage of plant available water due to the reasons discussed in the previous paragraph.

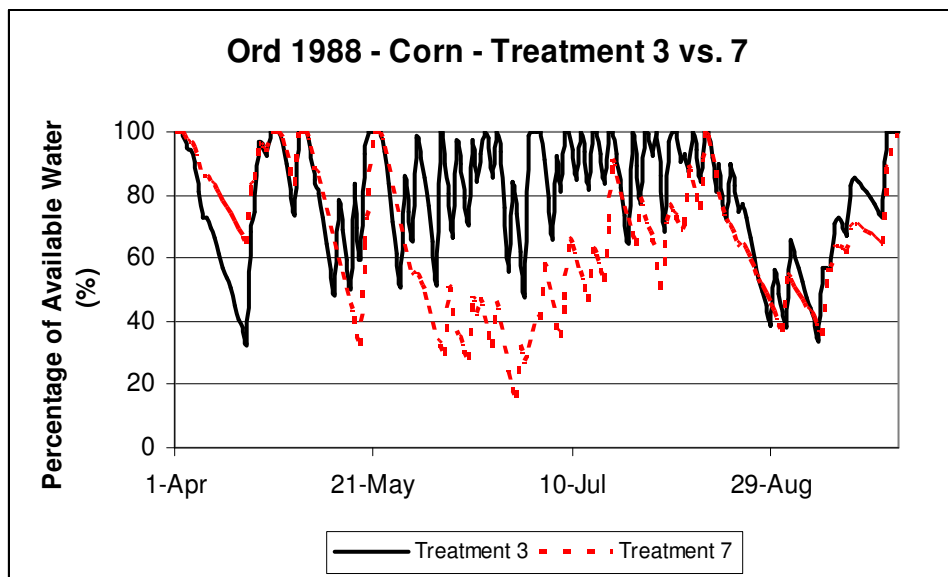


Figure 4.7: Percentage of available water during the 1988 growing season at Ord, NE for Treatments 3 and 7.

The average number of DBM was greatest for Treatments 1 and 7 (13 days) and was held to zero with Treatments 6 and 9. At Ord, as with all the other sites, an increase in DBM are a direct indicator of decreased relative yield. This validates our scheduling

software and insures that the right minimum allowable water balances have been set. An example of this shown in Figure 4.8 for Treatment 7. If the days of stress are limited to 15 or less the relative yield is maintained above 90%.

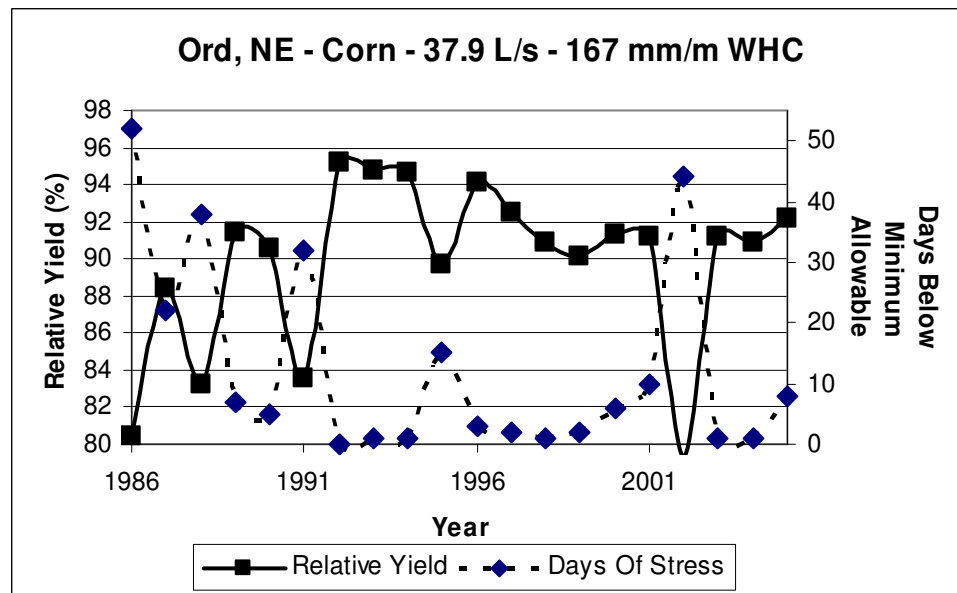


Figure 4.8: Relationship between relative yield and days under minimum allowable at Ord, NE for Treatment 7.

Relative yield was found to be significantly increased at Ord by increasing system pumping rate at the $p < 0.01$ level. It decreased significantly when increasing the soils WHC at the $p < 0.05$ level.

4.15 Rock Port, MO

Table 4.6: Rock Port, MO ASCE PM corn simulation averages.

Treatment	ET_c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Relative Yield
1	575	580	314	7	13	24	93
2	586	580	342	1	15	23	96
3	589	580	353	1	15	23	96
4	572	580	268	6	9	30	93
5	579	580	279	1	10	29	95
6	582	580	290	0	10	29	95
7	570	580	230	6	7	32	92
8	573	580	236	2	7	32	93
9	575	580	243	1	8	32	94

At this site the average seasonal ET_c demand was nearly equal to average seasonal rainfall amount (580 mm) for all treatments. This kept the average seasonal irrigation amounts relatively low compared to most of the other sites with a growing season from April 1 to September 30. Once again the largest average seasonal irrigation occurred with Treatment 3 (353 mm) and the smallest amount occurring using Treatment 7 (230 mm). The ratio of the seasonal irrigation amount applied to the 167 mm/m soil versus the 83 mm/m soil for all pumping rates was relatively small. Average ratios range from 0.69 for both the 50.5 and 63.1 L/s systems to 0.73 for the 37.9 L/s systems. In comparison, the average ratios at the Akron, CO site range from 0.90 to 0.94 for the 50.5 and 37.9 L/s systems respectively (Figure 4.9). This is an indication that there is a larger amount of rainfall being lost to runoff and deep percolation on the coarse textured soils at the Rock Port, MO site.

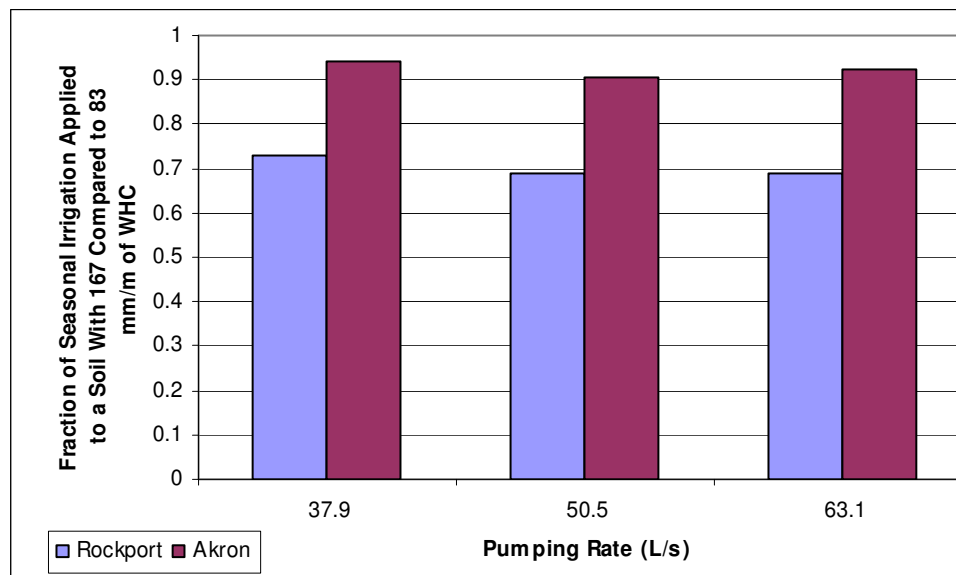


Figure 4.9: Ratio of seasonal irrigation applied to a soil with 167 mm/m of WHC compared to a soil with 83 mm/m of WHC for all pumping rates simulated.

Average irrigation depth applied at this site ranged from 23 mm for Treatments 2 and 3 to the maximum depth that is allowed to be applied by the system, 32 mm, for all treatments with 167 mm of WHC per meter of soil. Due to the large amount of seasonal rainfall the average DBM were minimized while maximizing the relative yield. The greatest average number of DBM occurred with Treatment 1 (7 days) while Treatment 6 averaged no days.

The lowest average relative yield (92%) occurred when implementing Treatment 7 with the highest taking place using Treatments 1 and 2 (96%). At the $p < 0.01$ level, relative yield significantly increased with increased pumping rate and decreased with increased soil WHC.

4.16 St. John, KS

Table 4.7: St. John, KS ASCE PM corn simulation averages.

Treatment	ET_c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Relative Yield
1	708	432	466	31	17	27	85
2	756	432	542	13	20	26	92
3	773	432	555	10	21	26	93
4	711	432	431	28	14	30	85
5	747	432	488	12	16	30	91
6	766	432	518	1	18	29	95
7	710	432	410	29	13	31	85
8	742	432	446	12	14	31	90
9	754	432	471	2	15	31	92

St. John, KS can be characterized as a site with relatively high ET demand and low rainfall during the growing season. The average seasonal ET_c amount (773 mm) is approximately 1.8 times the average seasonal rainfall of 432 mm. This fact led to a greater number of average DBM and lower average relative yield values than all the sites analyzed except Akron, CO. The treatments with a system pumping rate of 37.9 L/s all had the lowest average relative yield values of 85 %. Average relative yield was maximized with Treatment 6 (95 %). The relatively high ET demand and low rainfall also increased the average number of rotations the pivot made during the growing season along with the average seasonal irrigation amount. Treatment 3 had the greatest average seasonal irrigation depth of 555 mm and also the greatest number of rotations at the site with 21.

The worst case scenario occurred at this site in 2001. ET demand was high with little rainfall occurring during the critical stages of crop growth. From June 8 to

September 16 only 114 mm of rain fell in the area. The 37.9 L/s treatments were unable to keep up with these conditions which resulted in many DBM and reductions in relative yield. Treatment 4 had the greatest adverse reaction to the conditions. The same period mentioned earlier that received only 114 mm of rain experienced a cumulative ET deficit of 599 mm. The 37.9 L/s system was unable to supply enough irrigation in a timely manner for a soil with this WHC which resulted in there being 73 DBM and a relative yield of 74%.

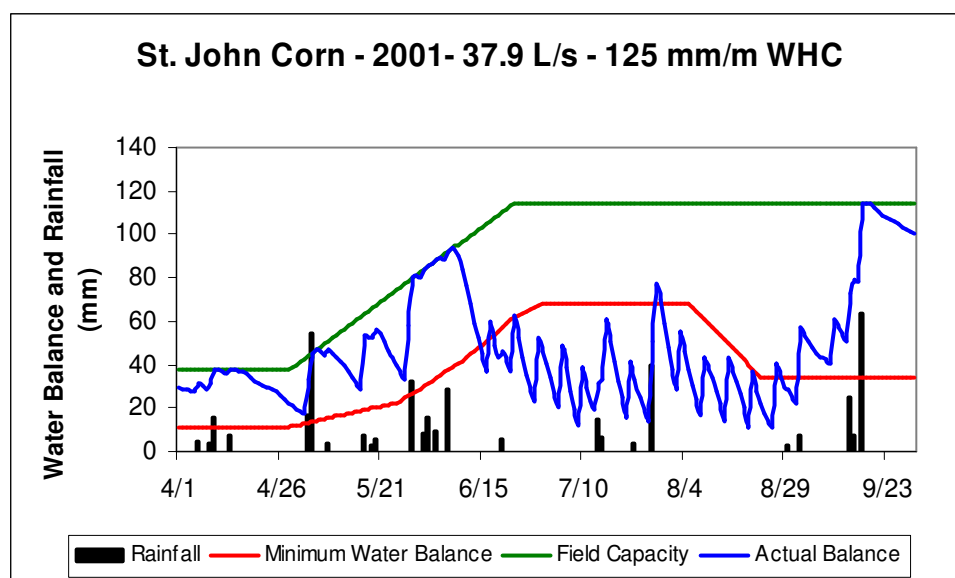


Figure 4.10: Tracking of actual water balance (blue line) during the 2001 corn growing season at St. John, KS using Treatment 4.

4.2 Corn Simulations using Jensen-Haise Evapotranspiration Equation

Simulations were conducted at the Brookings, SD and St. John, KS sites to determine the effects of using the Jensen-Haise (JH) equation to determine daily ET_r amounts instead of the ASCE PM equation. Due to time constraints, simulations were only conducted at these two sites. The Brookings site was chosen because it had relatively average seasonal ET_c amounts compared to the other sites in this study while the St. John site was chosen because it had comparatively high seasonal ET_c amounts.

4.20 Brookings, SD

Table 4.8: Brookings, SD Jensen-Haise corn simulation averages.

Treatment	ET_c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Relative Yield
1	492	431	282	3	11	25	94
2	497	431	309	1	13	23	96
3	499	431	314	1	14	23	96
4	486	431	242	3	8	30	93
5	490	431	252	1	9	28	94
6	492	431	262	0	9	28	95
7	480	431	227	5	7	32	91
8	483	431	230	1	7	32	92
9	485	431	233	0	7	32	93

At Brookings, the JH equation estimated a daily ET_r less than that when using the ASCE PM equation (Figure 4.11). This in turn led to lower values of seasonal ET_c .

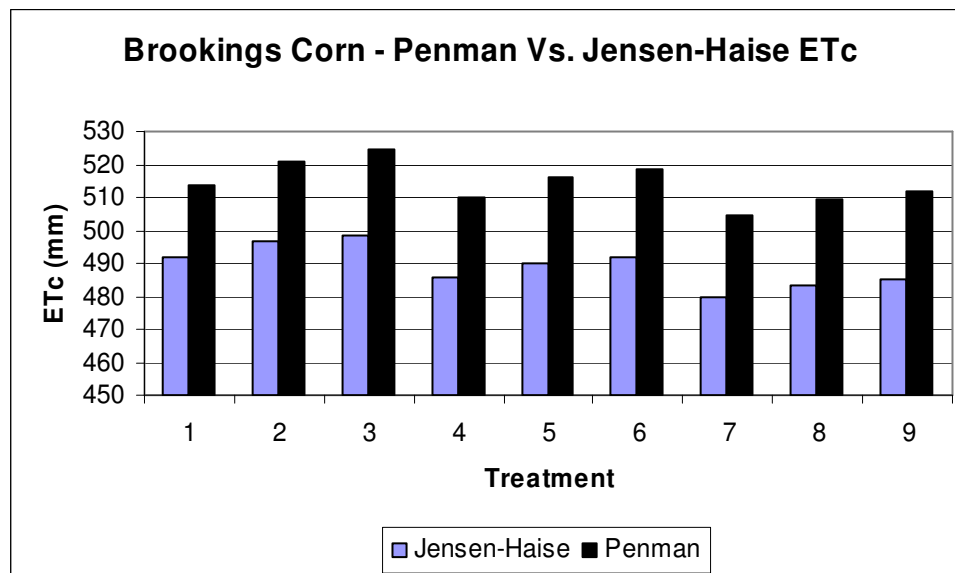


Figure 4.11: Average ET_c values using Jensen-Haise and ASCE Penman equations at Brookings, SD.

On average over the entire growing season, the JH equation estimated the ET_c amount to be an average of 5% less than the PM equation for all treatments with a standard deviation of 0.2%. This resulted in an average of 5% less total irrigation being applied to the field over the growing season.

The number of DBM dropped slightly using the JH equation when administering Treatments 1, 4, 7, and 8 (Figure 4.12). The lower seasonal irrigation and ET amounts did not translate into relative yield increases however, as the relative yield was identical for all simulations whether using the JH or PM equation to estimate ET_r.

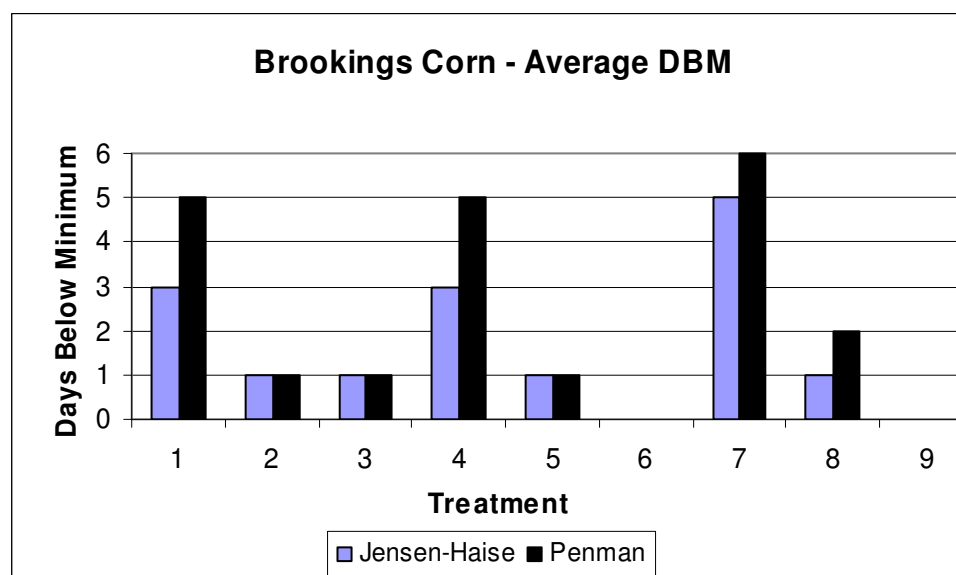


Figure 4.12: Comparison of average DBM using either JH or ASCE PM method of determining ET_r at Brookings, SD.

4.21 St. John, KS

Table 4.9: St. John, KS Jensen-Haise corn simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Relative Yield
1	661	432	424	22	16	27	89
2	693	432	487	5	19	25	95
3	704	432	501	4	20	25	95
4	659	432	389	22	13	30	88
5	685	432	431	4	14	30	93
6	693	432	447	0	15	29	95
7	655	432	363	23	11	32	88
8	676	432	386	5	12	32	92
9	684	432	404	0	13	32	93

The JH equation at St. John, KS estimated crop seasonal evapotranspiration to be an average of 8% less than when using the ASCE PM equation. This resulted in an

average of only 89% of the total seasonal irrigation being applied for all treatments compared to the PM simulations.

Unlike the Brookings site, the method of determining ET_r had an effect for all treatments on the number of days under the minimum allowable limit and also the relative yield (Figure 4.13). When using the JH instead of the PM equation, the number of DBM using Treatment 1 was decreased from 31 to 22. Treatments 6 and 9 had no DBM using the JH compared to 2 and 1 using the PM. Relative yield values averaged an increase of 2% when using this method. The greatest relative increase occurred with Treatment 1 (4%).

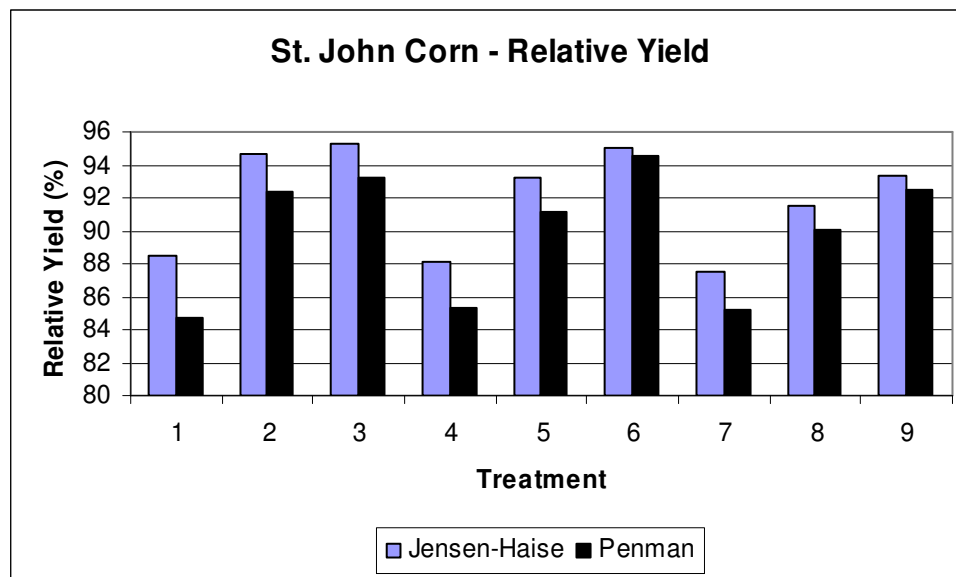


Figure 4.13: Comparison of relative yields obtained at St. John, KS for all treatments using either the JH or ASCE PM method of estimating ET_r .

4.3 Soybean Simulations

4.30 Akron, CO

Table 4.10: Akron, CO soybean simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)
1	610	286	422	30	15	29
2	674	286	500	13	18	28
3	705	286	514	10	18	28
4	610	286	414	34	14	31
5	663	286	476	14	16	31
6	691	286	510	3	17	30
7	605	286	400	37	13	32
8	653	286	460	16	15	31
9	677	286	491	3	16	31

For all treatments at this site, the ET_c demand was more than double the average seasonal rainfall (286 mm). To offset the demand, the irrigation scheduling software simulated average seasonal application depths from 400 mm (Treatment 7) to 514 mm (Treatment 3).

DBM increased with increased soil WHC for the 37.9 L/s and 50.5 L/s treatments and decreased for the 63.1 L/s treatments. Treatment 1 had 30 DBM while Treatment 7 had an average of 37 days. Similarly Treatment 2 had an average of 13 DBM, which increased to 16 days for Treatment 8. The treatments that simulated a pumping rate of 63.1 L/s dropped the average DBM from ten to three when going from a soil WHC of 83 mm/m to 167 mm/m. The treatments that simulated a pumping rate of 63.1 L/s treatments were able to lower the number of DBM. This was due to the fact that the increased pumping capacity allowed the system to overcome the increased volume of

water needed to maintain the actual balance above minimum allowable, which occurs when increasing the soil water holding capacity.

4.31 Ames, IA

Table 4.11: Ames, IA soybean simulation averages.

Treatment	ET _c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)
1	451	516	202	2	8	24
2	457	516	221	1	9	23
3	458	516	223	0	10	23
4	447	516	176	2	6	28
5	450	516	179	0	6	27
6	453	516	190	0	7	28
7	443	516	157	2	5	29
8	444	516	161	1	5	29
9	447	516	164	0	5	28

The average seasonal irrigation amounts at this site were the lowest of all the sites that had the same simulated season length. This is explained by the fact that the average seasonal rainfall (516 mm) was greater than the seasonal ET_c amount for all the treatments. This fact also explains why the average maximum DBM were held to two, which occurred in all treatments with a 37.9 L/s pumping rate.

The soybean growing season in 1989 at Ames has some interesting features. First of all, there were 914 mm of rainfall which is nearly 400 mm greater than average. In spite of this fact, the irrigation scheduling software instructed the irrigator to apply between 127 and 197 mm of water. A closer look at the timing and depth of the rainfall events reveals why this occurred.

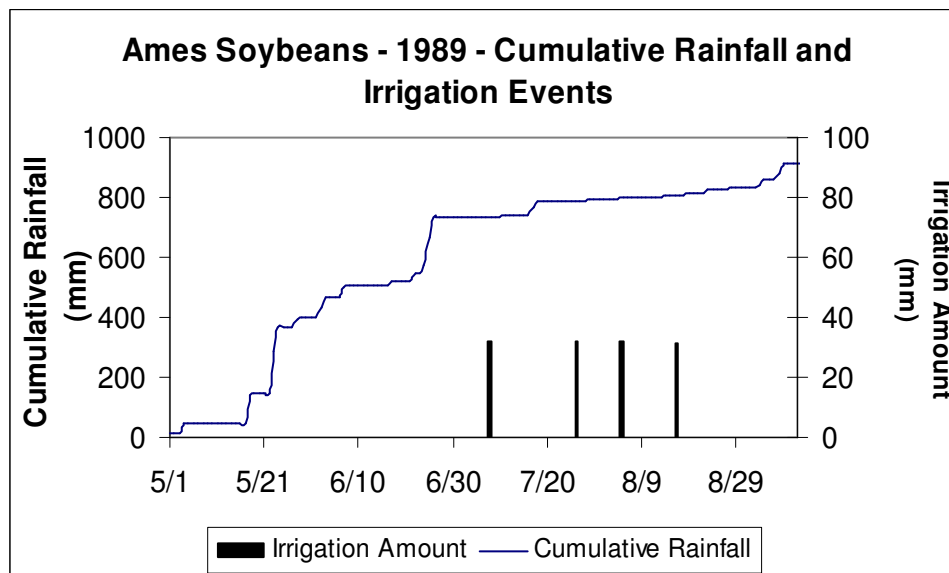


Figure 4.14: Accumulated seasonal rainfall and irrigation events throughout the 1989 soybean growing season at Ames, IA.

Figure 4.14 shows that nearly 750 mm of 914 mm, or 82% of seasonal rainfall, had accumulated before June 26. If the crop was not drowned out by this time in the growing season, then this is the time leading up to the most critical stage in soybean plant development. The scheduling software assumes that all previous rainfall events that were greater than field capacity were lost and it instructs the irrigation system to apply amounts to help maintain the actual soil water content above the minimum allowable.

4.32 Brookings, SD

Table 4.12: Brookings, SD soybean simulation averages

Treatment	ET _c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)
1	410	325	230	3	9	25
2	418	325	240	0	10	24
3	419	325	240	0	10	23
4	405	325	207	2	7	30
5	409	325	211	0	7	29
6	412	325	216	0	7	29
7	398	325	195	3	6	32
8	397	325	196	0	6	32
9	404	325	203	0	6	32

Even though the average seasonal rainfall is less than the average seasonal ET_c amount for all treatments, the software was able to schedule irrigations adequately enough on the average to eliminate all DBM for treatments with pumping rates of 50.5 L/s or greater. The 37.9 L/s treatments had a maximum of three DBM for Treatment 1. Figure 4.15 compares the seasonal ET_c found in all years for Treatments 4, 5, and 6.

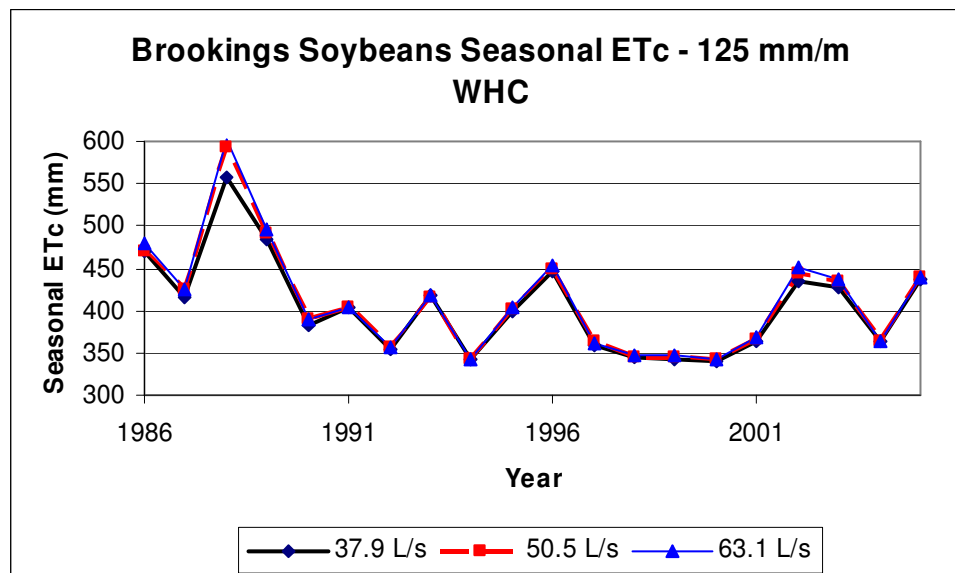


Figure 4.15: Average seasonal ET_c values obtained using Treatments 4-6 at Brookings, SD.

As a general rule, all the system pumping rates were able to maintain an equivalent seasonal ET_c total by keeping the soil moisture balance nearly equal throughout the growing season. There are a few years in which you can see the 37.9 L/s system has a lower seasonal ET_c which occurred because it was unable to keep up with the full ET_c demand of the season, allowing the actual soil moisture level to drop below the minimum allowable. This is especially evident in 1988, when near record temps in the month of July pushed the seasonal ET_c amount to over 100 mm above the average. Seasonal irrigation amounts ranged from an average of 195 mm (Treatment 7) to 240 mm (Treatment 3).

4.33 Oakes, ND

Table 4.13: Oakes, ND soybean simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)
1	329	267	194	2	8	25
2	333	267	204	0	9	23
3	334	267	208	0	9	23
4	314	267	173	0	6	28
5	327	267	190	0	7	29
6	328	267	189	0	7	29
7	319	267	174	1	6	32
8	320	267	178	0	6	32
9	322	267	182	0	6	32

All treatments with a pumping rate greater than or equal to 50.5 L/s were able to eliminate, on average, all the DBM. Treatment 1, with a pumping rate of 37.9 L/s, had the maximum average number of DBM (two). Treatments 7, 8, and 9 all applied the maximum depth of irrigation possible (32 mm) an average of six times per growing season. In contrast, Treatment 1 applied on average 25 mm of water each of the eight applications while both Treatment 2 and 3 applied 23 mm an average of nine times each summer.

The irrigation scheduling software directs the system to apply smaller amounts of water more often to soils with the lower water holding capacities so that the balance does not exceed field capacity. This is demonstrated in 1992 when comparing the irrigation depths applied with Treatment 3 compared to Treatment 9 (Figure 4.16). Treatment 3 had seven different irrigation events that applied a total of 157 mm of water for an

average of 22 mm per event. In Treatment 9, there were only three irrigation events in which a total of 95 mm of water was applied for an average application depth of 32 mm.

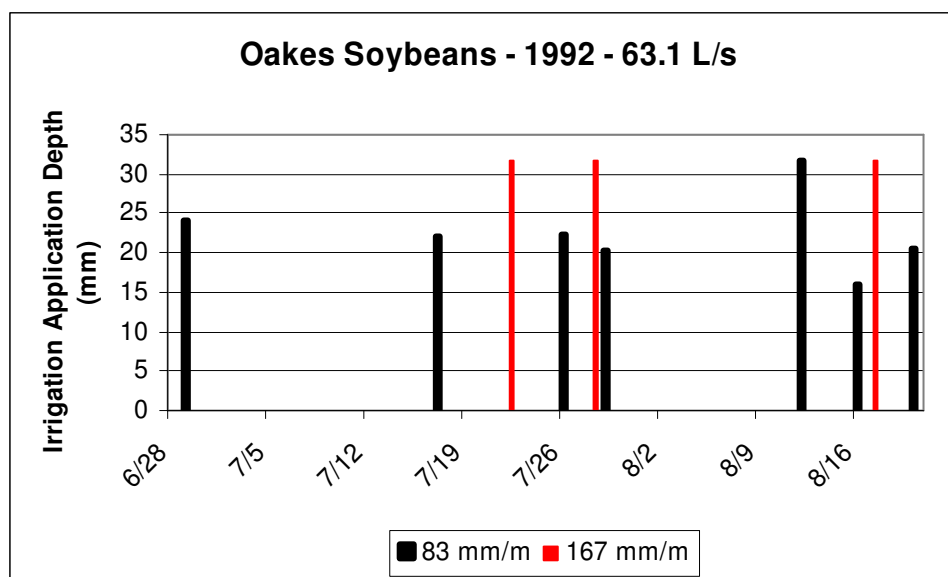


Figure 4.16: 1992 seasonal rainfall and irrigation events simulated at Oakes, ND using Treatments 3 and 9.

4.34 Ord, NE

Table 4.14: Ord, NE soybean simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)
1	498	355	293	9	11	27
2	515	355	319	2	12	25
3	521	355	324	1	13	25
4	495	355	263	7	9	30
5	505	355	283	2	9	30
6	510	355	288	0	10	30
7	485	355	251	9	8	30
8	496	355	263	2	8	30
9	501	355	269	0	9	30

A 63.1 L/s system was able to, on average, maintain the water balance above the minimum allowable when applying to a soil with 125 or 167 mm/m of WHC. A system with this pumping rate only allowed an average of one day below the minimum allowable on a soil able to hold 83 mm of water per meter of soil. A 50.5 L/s system averaged only two days under the minimum allowable for all the soil types simulated. In contrast, the simulations with a pumping rate of 37.9 L/s averaged seven days of stress on a soil with 125 mm/m of WHC and nine days on soils with 83 and 167 mm/m of WHC.

The two highest pumping rate systems were even able to sufficiently keep up with ET demand in years with well below normal precipitation. This is demonstrated by the simulations conducted using the weather data from 1986 (Figure 4.17). During the soybean growing season, only 156 mm of rain fell, which is nearly 200 mm below the 20 year average for this site. Despite this fact, all the treatments with a pumping rate of 63.1 L/s had no days in which the soil water balance dropped below minimum allowable while the treatments with a pumping rate of 50.5 L/s ranged from zero days (Treatment 5) to only 4 days (Treatment 8). On the other hand, treatments with a pumping rate of 37.9 L/s had from 26 days (Treatment 1) to 43 days (Treatment 7) that the water balance dropped below the minimum allowable.

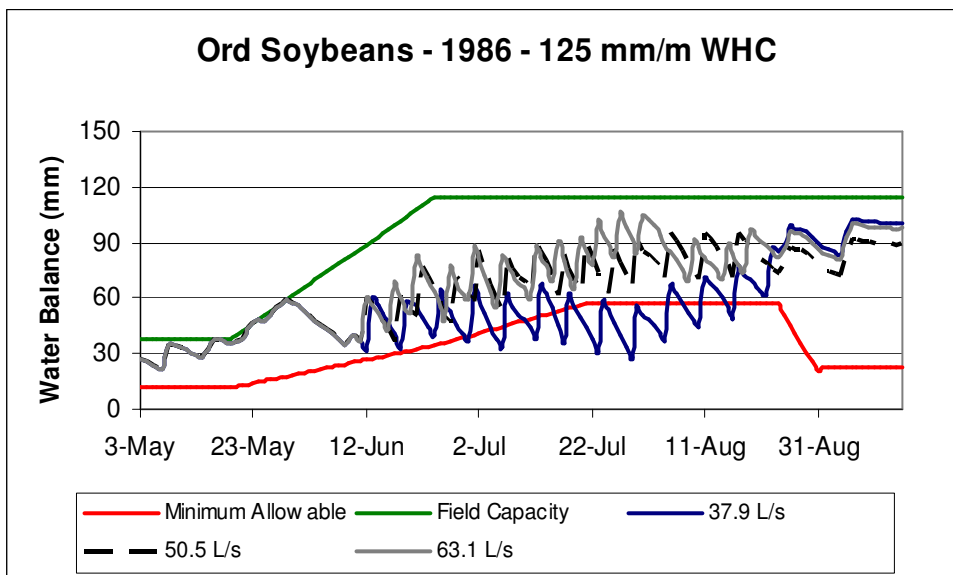


Figure 4.17: Tracking of soil water balance during the 1986 soybean growing season at Ord, NE for Treatments 4-6.

Average seasonal irrigation amounts varied from 324 mm using Treatment 3 to 251 mm with Treatment 7. The number of seasonal irrigation events ranged from eight (Treatments 7 and 8) to 13 (Treatment 3).

4.35 Rock Port, MO

Table 4.15: Rock Port, MO soybean simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)
1	464	463	247	5	10	26
2	474	463	266	0	11	24
3	477	463	271	0	11	24
4	462	463	217	4	7	30
5	467	463	229	0	8	30
6	470	463	235	0	8	29
7	455	463	198	5	6	32
8	460	463	206	1	7	31
9	462	463	212	0	7	31

Treatments 1, 4, and 7 averaged five, four, and five days respectively under minimum allowable at Rockport. Treatment 8 is the only other treatment that averaged any days under minimum allowable (one day). This is an indication that the 37.9 L/s system is the only one of those simulated that had difficulty keeping up with ET demand. Figure 4.18 tracks the seasonal ET_c totals for all simulations that were performed on a soil with 83 mm/m of WHC for each year analyzed. It indicates that Treatment 1 does not keep an equivalent soil water balance to Treatments 2 and 3 when ET_c demand is high. A noticeable difference is seen in the years 2001 – 2003 and 2005.

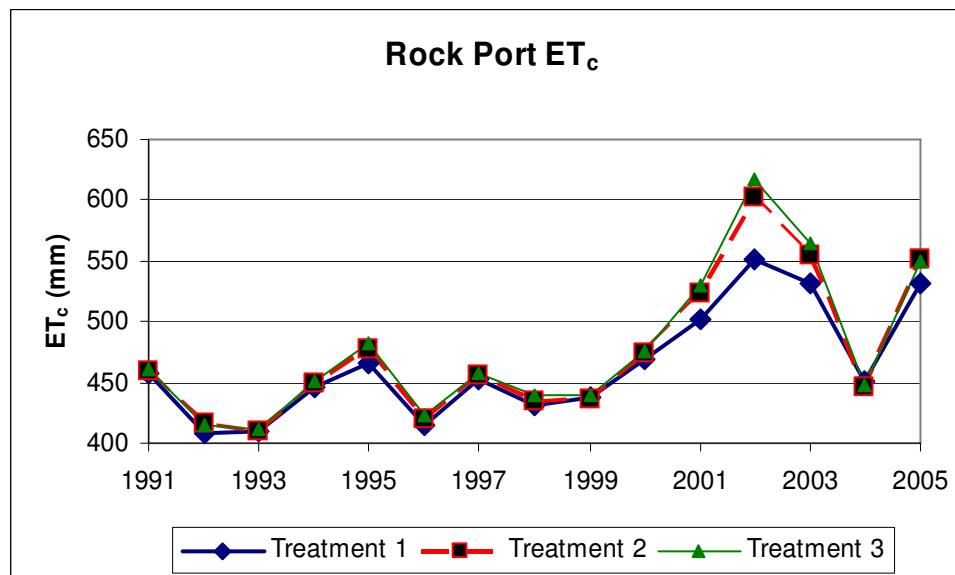


Figure 4.18: Comparison of seasonal ET_c values simulated at Rock Port, MO using Treatments 1-3.

The years identified above in which the 37.9 L/s system could not keep up with the ET demand could be identified by looking at a histogram of the DBM for the same time period. In all the years except those mentioned above, this pumping rate was able to limit the DBM to three or less. In 2001-2003 and 2005, systems with a 37.9 L/s pumping rate were not able to properly limit the DBM and there were a total of 12, 23, 14, and eight days, respectively, in these years (Figure 4.19).

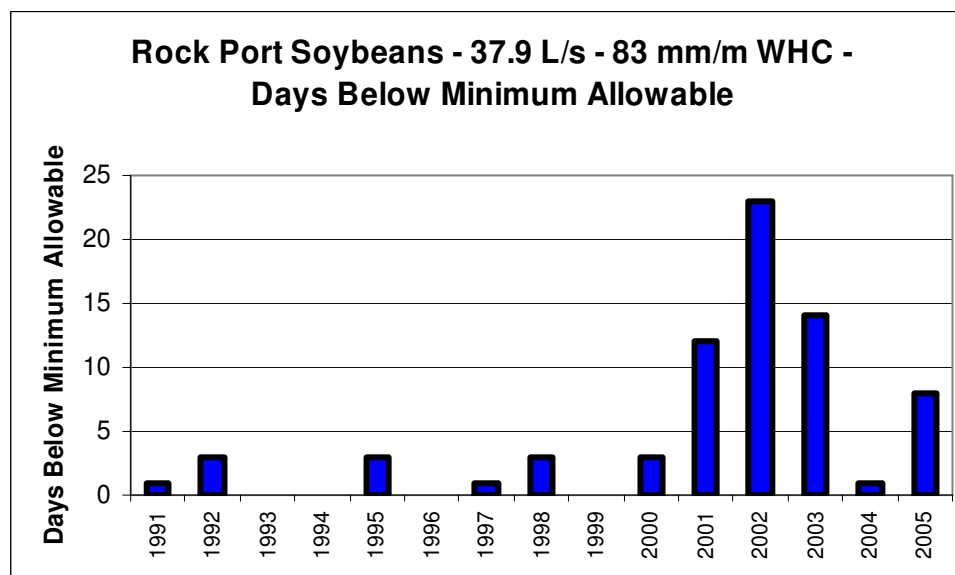


Figure 4.19: Seasonal DBM using Treatment 1 on soybeans at Rock Port, MO.

4.36 St. John, KS

Table 4.16: St. John, KS soybean simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)
1	576	359	366	24	13	29
2	618	359	427	8	15	28
3	638	359	438	6	16	28
4	575	359	339	25	11	31
5	610	359	387	8	13	31
6	628	359	417	1	14	31
7	573	359	318	25	10	32
8	602	359	367	9	12	32
9	616	359	385	2	12	32

Due to the low ratio of rainfall to ET demand at St. John, the greater pumping capacity that the system has, the fewer number of DBM occurred. Treatment 1 averaged

three times the average number of DBM as Treatment 2 and four times the average of Treatment 3 (Figure 4.20).

Examining the total seasonal DBM on a year-to-year basis for all pumping rates on a soil with a WHC of 125 mm/m makes apparent the importance of having a higher capacity system at this location. The average DBM were 25, eight, and one for Treatments 4, 5, and 6 respectively.

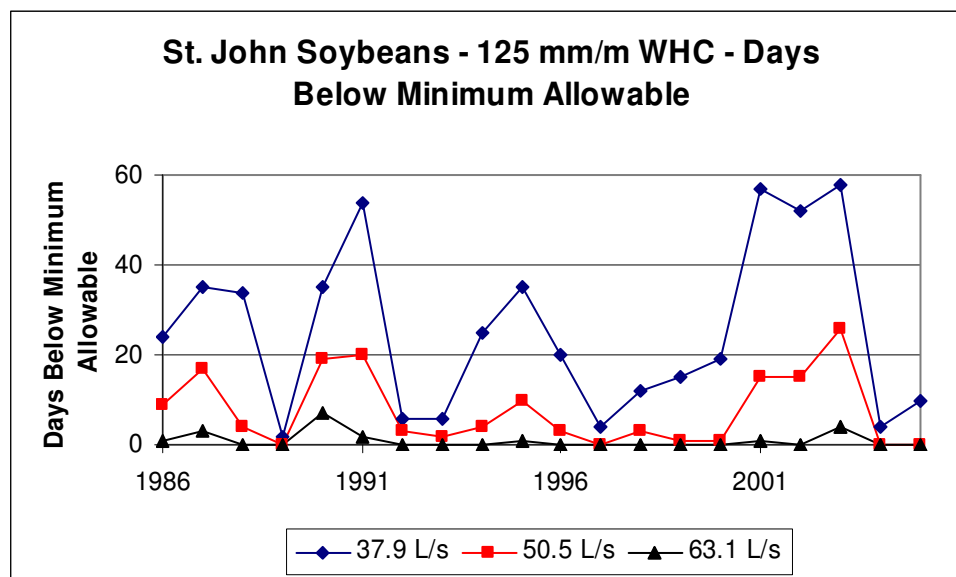


Figure 4.20: DBM for Treatments 4-6 at St. John, KS.

There are some years in which the grain yield may be adversely affected by having a 37.9 L/s system compared to a 50.5 or 63.1 L/s system. One case in point is 2003. The DBM for the year were 58, 26, and four for the 37.9, 50.5, and 63.1 L/s systems, respectively. For many of the 56 DBM using the 37.9 L/s system, the actual balance was below 40 mm, which was only 35% of WHC once the rooting depth has reached its maximum. This could cause considerable stress in the crop and lead to large yield reductions. On the other hand, of the four DBM recorded for the 63.1 L/s system,

two of the days were before the assumed critical period of development. The other two days dropped the actual balance to 49% and 44% of field capacity, which is just below the minimum allowable balance of 50% of field capacity (Figure 4.21).

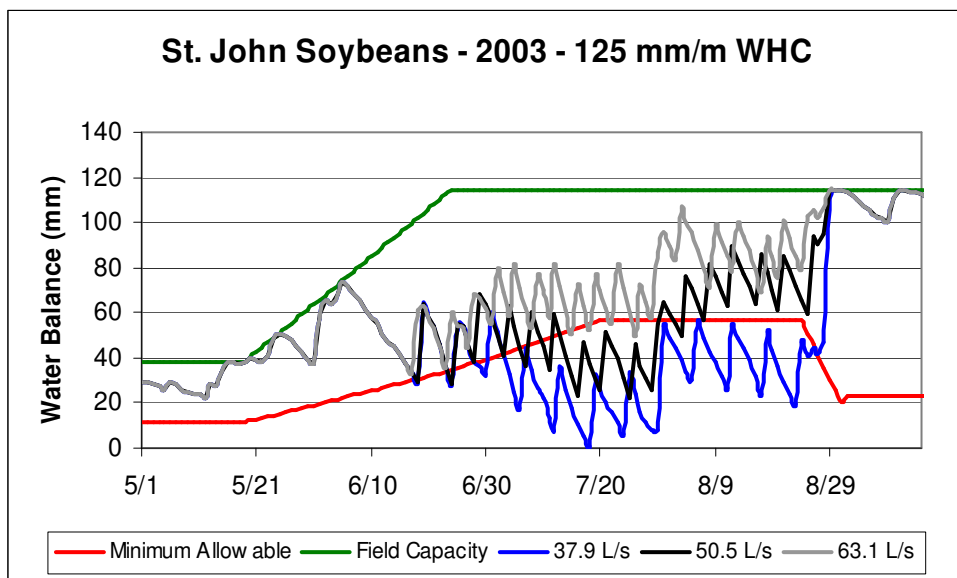


Figure 4.21: Simulated soil water balance for Treatments 4-6 during the 2003 soybean growing season at St. John, KS.

4.4 Potato Simulations

4.40 Akron, CO

Table 4.17: Akron, CO potato simulation averages.

Treatment	ET _c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Excess Water By Irrigator (mm)
1	612	303	432	45	18	24	36
2	651	303	507	26	23	22	91
3	662	303	544	17	27	20	140
4	621	303	423	38	17	25	22
5	654	303	475	17	20	23	43
6	664	303	500	8	24	21	77
7	627	303	411	35	16	25	6
8	655	303	454	12	19	24	18
9	664	303	476	4	22	22	35

The potato growing season at this site was assumed to start on April 1 with a harvest date of September 15. The average seasonal ET_c demand for all treatments was more than double the average seasonal rainfall (303 mm). Average seasonal irrigation amounts ranged from 411 mm (Treatment 7) to 544 mm (Treatment 3).

The pumping rate of the system along with the soil water holding capacity played major roles in the number of days the crops actual water level was below the minimum allowable during the season. A soil able to retain 83 mm of water per meter depth of soil had an average of 16, 26, and 45 days under the minimum allowable for Treatments 3, 2, and 1, respectively. In comparison, a soil with a WHC of 167 mm/m of soil had an average of 4, 12, and 35 days under the minimum allowable using Treatments 9, 8, and 7, respectively.

The challenge to scheduling irrigations for potatoes was to irrigate enough to limit the number of days in which the soil water balance drops below minimum allowable while at the same time not applying extra water that will push the actual balance over field capacity in any section of the field. This was difficult because the WHC range between field capacity and the minimum allowable balance is small due to the shallow rooting depth of the potato and its susceptibility to moisture stress.

For example, consider potatoes planted in a soil with a WHC of 83 mm/m. When the potato reaches its critical developmental stage, the rooting depth was assumed to be 0.6 m giving the soil a total WHC of 51 mm. During this stage, the minimum allowable water level was maintained at 70% of field capacity (35 mm). This means that the soil water balance was maintained above 35 mm to minimize crop water stress and below 51 mm to avoid excess water application. It was not uncommon to have between seven and nine millimeters of ET_c /day during this part of the growing season. Thus, the pivot may need to apply up to 18 mm every two days to avoid stressing the crop. Since there was only 15 mm between the minimum allowable water balance and field capacity, the crop would have to be slightly over-watered to avoid stress or slightly under-watered to avoid inducing water losses. Another problem is that the low pumping rate of some systems may not allow them to apply the depth of water needed at the frequency required. The irrigation scheduling simulation software was designed to avoid crop stress, which may cause some water losses during the growing season.

4.41 Ames, IA

Table 4.18: Ames, IA potato simulation averages.

Treatments	ET _c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Excess Water By Irrigator (mm)
1	443	601	228	15	12	19	35
2	446	601	254	11	14	18	54
3	447	601	254	8	15	17	57
4	445	601	208	9	10	20	24
5	448	601	218	5	12	18	28
6	448	601	219	4	12	17	24
7	446	601	189	6	9	21	12
8	449	601	200	3	10	19	17
9	449	601	200	1	11	17	12

Seasonal rainfall at Ames averaged approximately 1.4 times the ET_c demand for all potato treatments. Average irrigation application depths were low, ranging from 17 mm (Treatments 3, 6, and 9) to 21 mm (Treatment 7). There was no significant difference among the average seasonal ET_c amounts of all the treatments (Figure 4.22). The similar average seasonal ET_c amounts indicated that the lower pumping rate systems were able to keep up with the crops water needs just as well as the higher pumping rate systems.

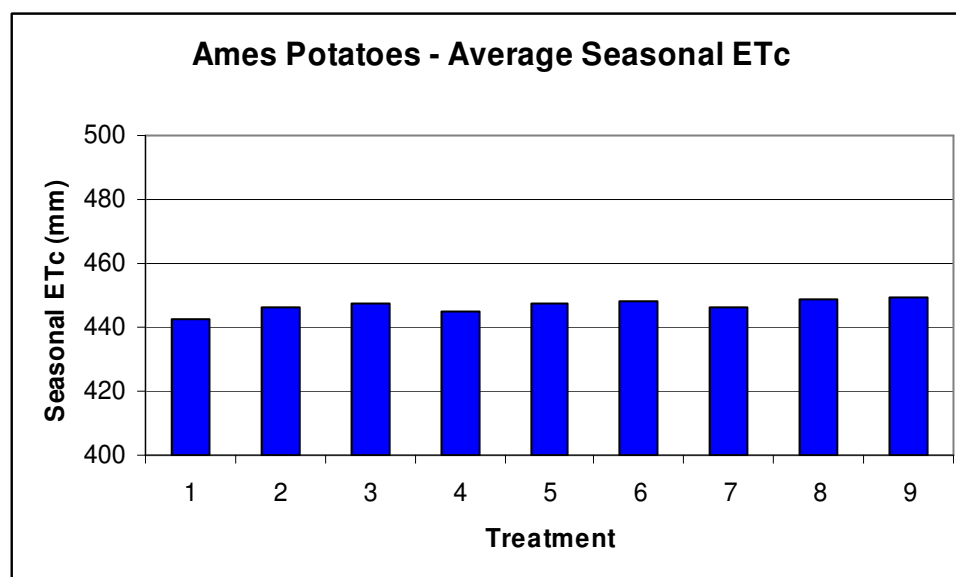


Figure 4.22: Seasonal average ET_c values for potatoes at Ames, IA for all treatments.

Figure 4.23 shows that when the average days in which the actual balance fell below the minimum allowable, the greater the pumping rate and water holding capacity of the soil, the fewer days there were below minimum allowable. This can be explained by the fact that during the critical stage of growth for potatoes, the minimum allowable water balance in the soil is set to 70% of field capacity compared to 50% for soybeans and 60% for corn. Any drop below that level, however small, is considered by the software to be a day below the minimum allowable. The plant available water coefficient (K_a) only drops to 0.92 when the actual water balance becomes 70%. This explains why using seasonal ET_c amounts to determine if all pumping rates are equally able to manage the water balance above field capacity is not an effective method for potatoes.

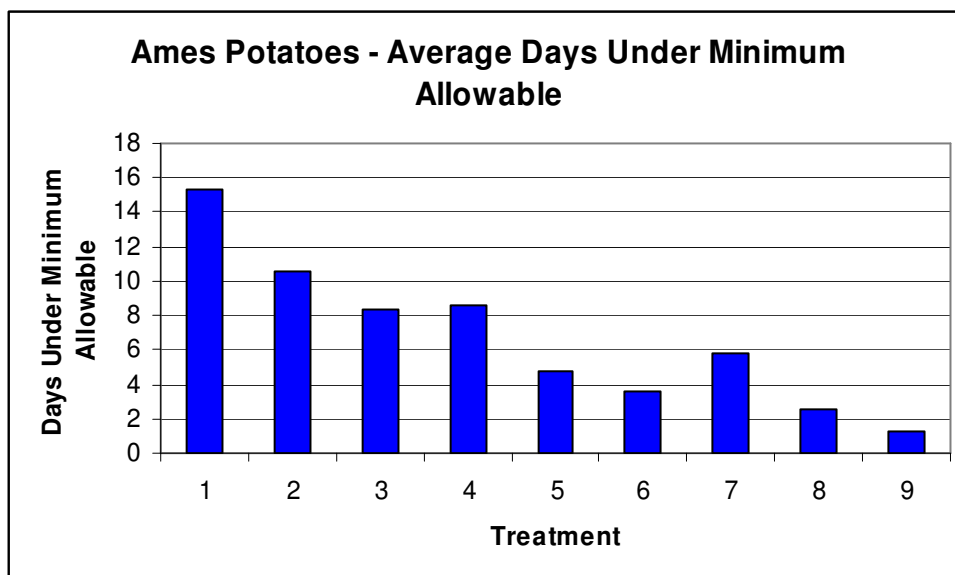


Figure 4.23: Seasonal average days under minimum allowable at Ames, IA for all treatments.

4.42 Brookings, SD

Table 4.19: Brookings, SD potato simulation averages.

Treatment	ET _c (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Excess Water By Irrigator (mm)
1	408	390	235	16	12	19	35
2	412	390	250	9	14	18	46
3	413	390	255	8	15	17	54
4	410	390	214	9	11	20	17
5	413	390	224	5	12	18	22
6	414	390	226	3	13	17	21
7	411	390	199	6	10	20	5
8	413	390	212	3	11	19	10
9	413	390	207	2	12	17	8

Average seasonal irrigation amounts ranged from 255 mm using Treatment 3 to 199 mm using Treatment 7. As with the Ames, IA site, the seasonal ET_c amounts were

not significantly different for all the treatments. Average irrigation depths applied were identical to the Ames site for all treatments except for Treatment 7 which averaged 21 mm at Ames and 20 mm at Brookings.

As discussed earlier, the scheduling software's main objective with potatoes is to minimize DBM which often resulted in over applications of water. The excess water applied by the irrigation system was any amount of water above field capacity that occurs on the day in which the irrigator passes the section being analyzed. The difference between the excess water applied and the seasonal irrigation amount is then divided by the seasonal irrigation amount to determine the seasonal application efficiency. The seasonal application efficiency generally becomes greater as the WHC of the soil increases and pumping rate decreases. The average seasonal application efficiencies for all treatments are shown in Figure 4.24. The potato crop was able to utilize 98% of the water applied using Treatment 7 compared to 79 % using Treatment 3.

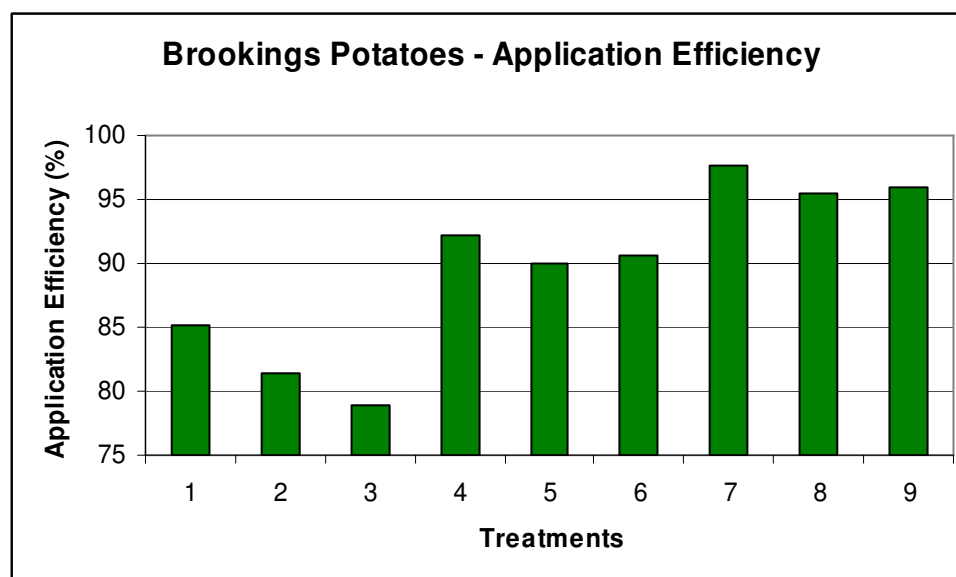


Figure 4.24: Average irrigation application efficiency on potatoes grown in Brookings, SD for all treatments.

The cost of more effectively using water resources in potato irrigation is often an increase in the number of days in which the actual water balance drops below the minimum allowable balance in a season. This is demonstrated when comparing Treatment 1 to Treatment 3 (Figure 4.25). Although Treatment 1 had a higher average application efficiency, 85% compared to 79%, Treatment 3 had only an average of eight days under minimum allowable compared to nearly 16 with Treatment 1.

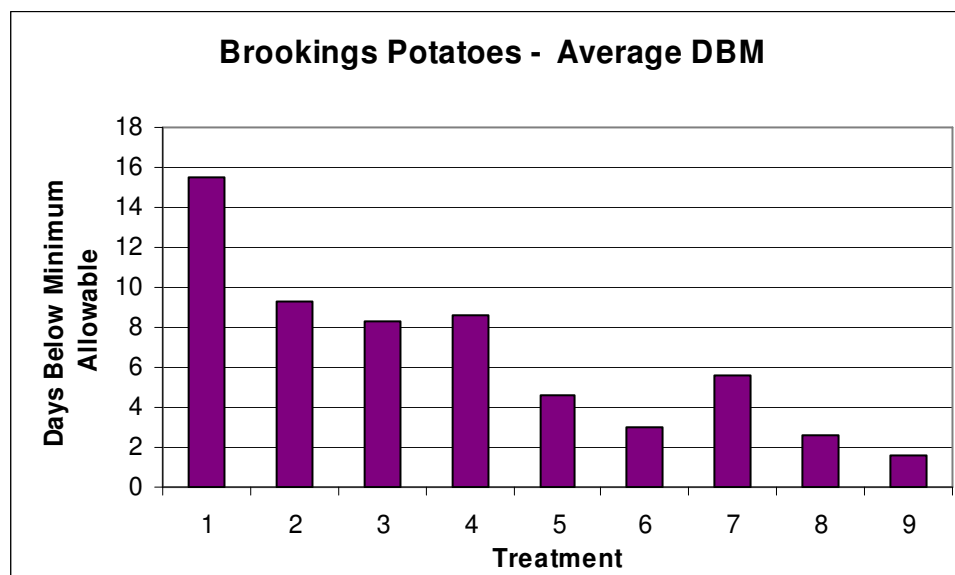


Figure 4.25: Average DBM for Brookings, SD potato crop.

4.43 Oakes, ND

Table 4.20: Oakes, ND potato simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Excess Water By Irrigator (mm)
1	362	339	217	14	11	19	32
2	364	339	232	10	13	18	44
3	365	339	232	8	14	16	43
4	364	339	199	8	10	19	14
5	366	339	214	5	12	18	24
6	366	339	211	4	13	17	21
7	364	339	190	5	10	20	6
8	366	339	197	2	11	18	11
9	366	339	193	2	11	17	5

Due to the shorter growing season, the number of irrigation events at Oakes was less than all the other sites analyzed. The pivot passed this section an average of only ten

times for both Treatments 4 and 7. The largest number of irrigation events took place an average of 14 times using Treatment 3.

The average irrigation depth applied ranged from 16 mm for Treatment 3 to 20 mm for Treatment 7.

When looking at each of the soil types individually, the treatments with a pumping rate of 50.5 L/s averaged a slightly greater average seasonal irrigation depth than the treatments with pumping rates of 63.1 L/s. It would seem that the higher pumping rate would be able to apply more water to keep up with ET demand. A closer look at Treatments 5 and 6 from the year 1999 reveals why this may happen (Figure 4.26).

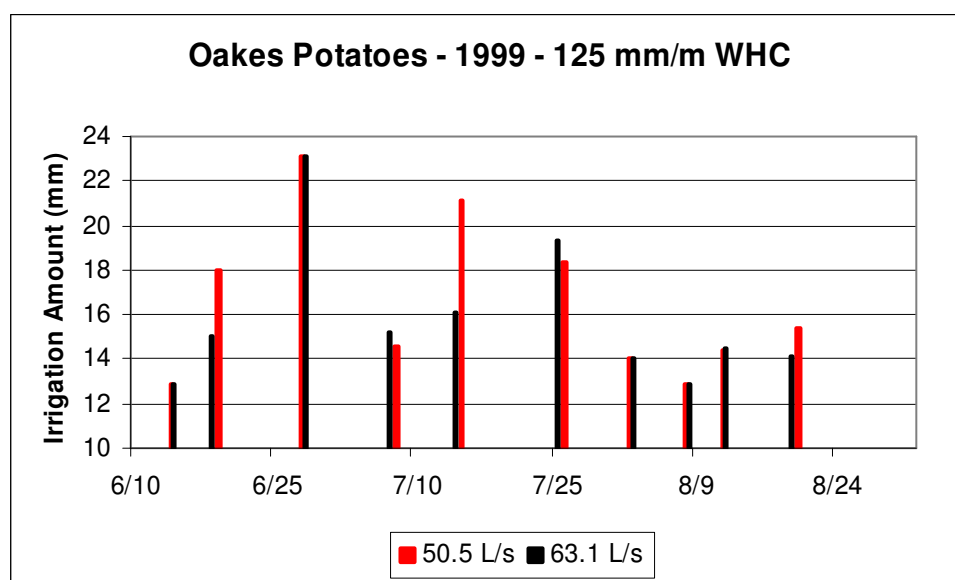


Figure 4.26: Comparison of timing and depth of irrigation applications for Treatments 5 and 6 during the 1999 potato growing season at Oakes, ND.

For the most part, the application depth is nearly equal throughout the growing season. Since a 50.5 L/s system must move slower than a 63.1 L/s system to apply the

same application depth, it takes more time to make a complete revolution (Figure 4.27). This increased time increases the amount of ET debt in the section. To compensate the irrigator must apply a greater amount of water to keep the soil water balance in the allowable range.

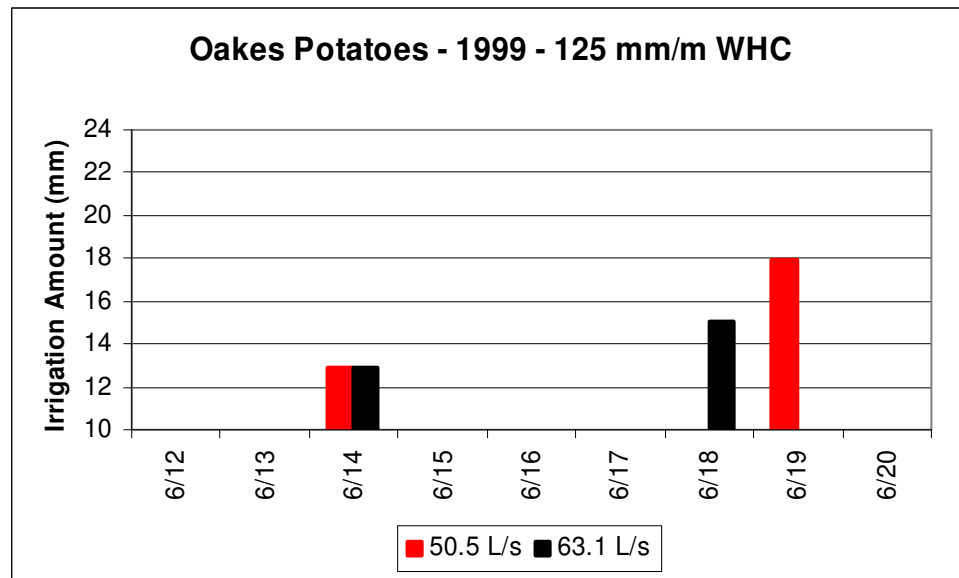


Figure 4.27: Closer look at timing and depth of irrigation applications for Treatments 5 and 6 during the 1999 potato growing season at Oakes, ND.

4.44 Ord, NE

Table 4.21: Ord, NE potato simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Excess Water By Irrigator (mm)
1	490	416	301	23	14	21	40
2	496	416	330	14	18	19	70
3	499	416	344	11	20	17	79
4	492	416	277	15	13	22	16
5	499	416	299	6	15	20	33
6	500	416	301	4	16	18	31
7	495	416	258	9	12	22	6
8	499	416	279	4	14	20	15
9	500	416	281	2	15	19	15

The average numbers of DBM were fewer at Ord as the WHC of the soil was increased. A 37.9 L/s system had a 61% decrease in the number of days under minimum allowable, from 23 to 9, when the WHC of the soil was increased from 83 to 167 mm/m. A 63.1 L/s system dropped the days under minimum allowable from 11 to two, an 82 % decrease, with the same increase in soil WHC.

The number of average irrigation events and seasonal irrigation amounts for each treatment are listed in Table 4.21. Both categories increased with pumping rate for a soil with a given water holding capacity.

4.45 Rock Port, MO

Table 4.22: Rock Port, MO potato simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Excess Water By Irrigator (mm)
1	457	544	255	17	13	20	42
2	462	544	274	10	15	18	49
3	463	544	283	8	17	17	56
4	460	544	230	10	11	21	18
5	463	544	249	5	13	19	35
6	464	544	248	3	14	17	29
7	462	544	215	6	10	20	11
8	464	544	225	2	12	19	12
9	464	544	226	2	13	18	14

The average seasonal rainfall amount (544 mm) is on averaged 1.2 times the ETc demand for all treatments. This led to relatively low average seasonal irrigation amounts compared with the other sites (Figure 4.28).

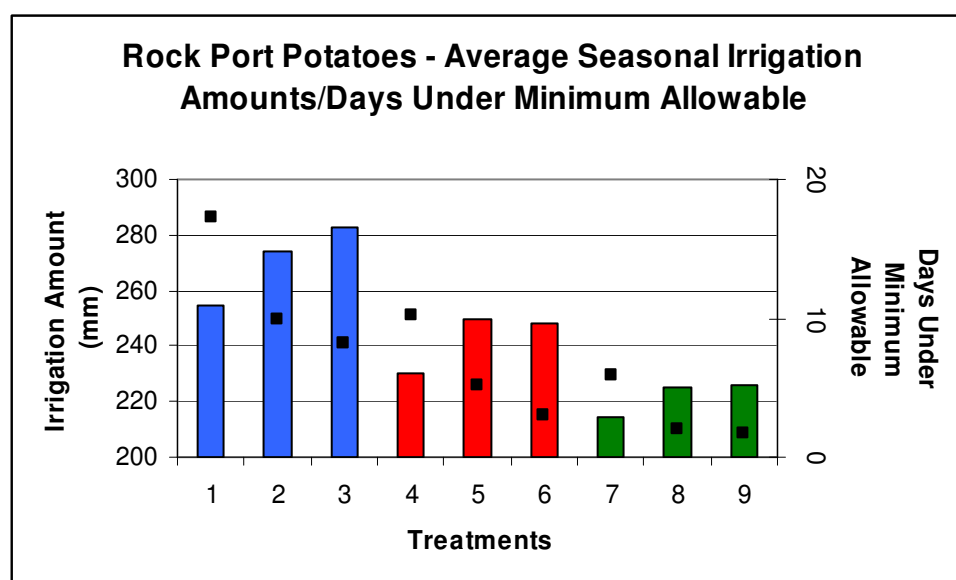


Figure 4.28: Average seasonal irrigation amount displayed in relation to the average days under minimum allowable that occurred at Rock Port, MO for all treatments.

Figure 4.28 displays the average seasonal irrigation amount for all the treatments on the left y-axis and the average DBM on the right y-axis. Seasonal irrigation amounts for a soil with a WHC of 83 mm/m of soil are represented in blue, 125 mm/m are in red, and 167 mm/m are in green. The average DBM are represented by the black dot above the corresponding treatment. Treatments 1, 4, and 7, which represent a pumping rate of 37.9 L/s, all have the lowest seasonal irrigation amounts and highest days under minimum allowable for each soil type compared to the other treatments.

The average number of seasonal irrigation events ranged from ten using Treatment 7 to 17 using Treatment 3. Excess water applied by the irrigator was kept relatively low on the soil with 167 mm/m of WHC compared to 83 mm/m soil type (Figure 4.29).

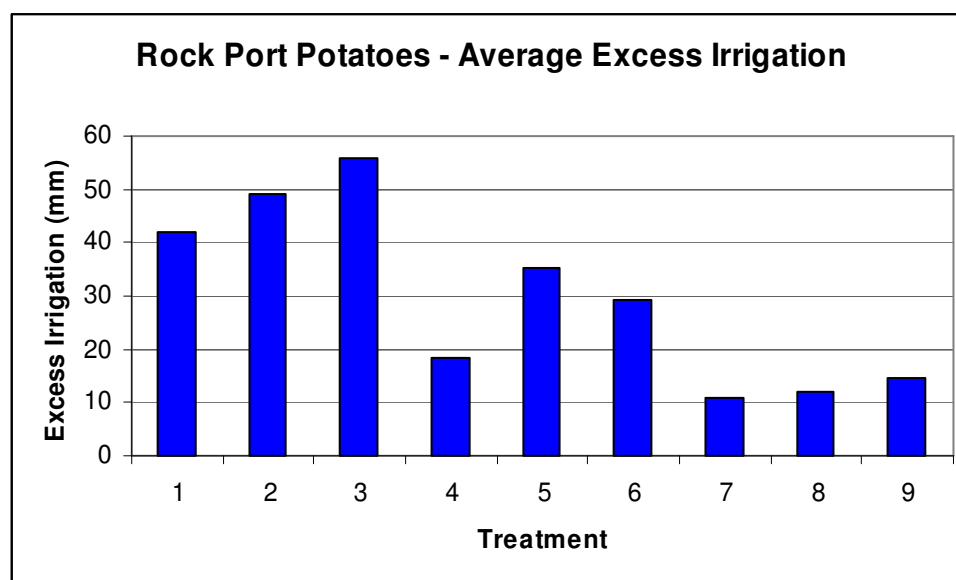


Figure 4.29: Average water depths in excess of field caused directly by an irrigation application for all treatments at Rock Port, MO.

4.46 St. John, KS

Table 4.23: St. John, KS potato simulation averages.

Treatment	ETc (mm)	Rainfall (mm)	Seasonal Irrigation Amount (mm)	DBM	Irrigation Events	Irrigation Depth (mm)	Excess Water By Irrigator (mm)
1	570	416	378	36	16	24	28
2	592	416	439	19	21	21	74
3	600	416	467	13	24	19	104
4	577	416	362	31	15	25	21
5	595	416	403	12	18	22	37
6	601	416	425	6	21	20	52
7	582	416	352	26	14	26	10
8	597	416	383	8	17	23	23
9	601	416	399	3	19	21	29

ETc demand at St. John was relatively high compared to most other sites analyzed with values ranging from 570 mm using Treatment 1 to 601 mm for both Treatments 6 and 9. The 37.9 L/s system was unable to keep up with ET demand at this site which is evidenced by the number of days under minimum allowable that occurred in Treatments 1, 4, and 7 compared to all other treatments (Figure 4.30).

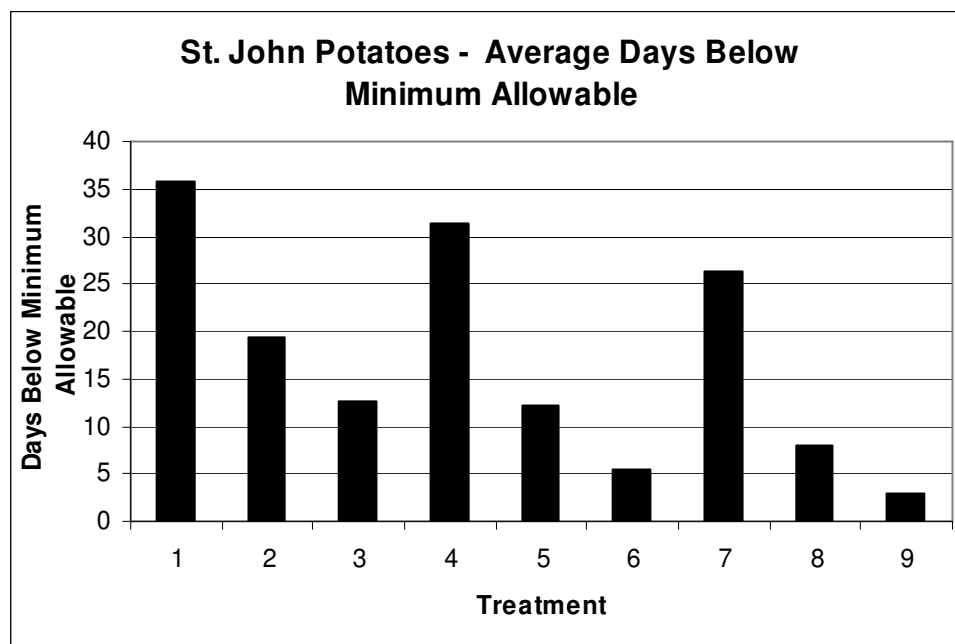


Figure 4.30: Average DBM for all treatments at St. John, KS.

When irrigating potatoes, the pivot is kept in near constant motion in order to maintain an adequate soil water balance. This is often even true in years with well above average amounts of rainfall. One example is 1993, a year in which 721 mm of rain fell. Although this is just over 300 mm greater than the seasonal average, the pivot still made an average of between 12 (Treatments 4 and 7) and 23 (Treatment 3) applications. Figure 4.30 shows the timing of the rainfall and irrigation during the critical stage of development which is considered to be from June 16 thru August 20. Irrigation amounts must be applied every 4-7 days to keep up with ET demand. Figure 4.31 demonstrates that the only thing that disrupts this irrigation pattern are rainfall events that are adequate enough to keep up with the ET demand.

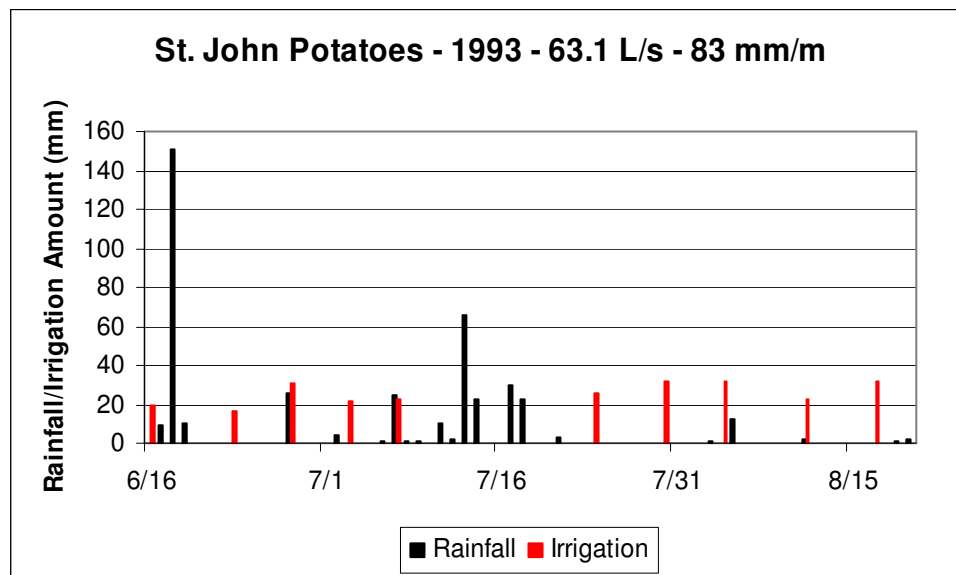


Figure 4.31: Timing and depth of irrigation and rainfall events using Treatment 3 at St. John, KS during the 1993 potato growing season.

CHAPTER V

SUMMARY AND CONCLUSIONS

Simulation software was developed to perform irrigation scheduling using 20 years of weather data for seven locations in the upper Great Plains. Simulations were conducted for three system pumping rates and three soil water holding capacities. Evapotranspiration was first estimated using the ASCE Penman Monteith alfalfa referenced equation at all sites for corn, soybeans, and potatoes. The Jensen-Haise equation was then used to estimate ET for a corn crop planted at the Brookings, SD and St. John, KS sites. A comparison of the seasonal irrigation data that resulted from using the two different methods of estimating ET was then completed. Minimum soil depletion allowances were set for various growth stages to minimize crop water stress.

The simulation model addressed the system operating limitations for the center pivot. Water could only be applied if the irrigation system was available at that location in the field. An ET forecasting scheme projected water use and operated the pivot to minimize crop water stress throughout the field.

The simulation model was able to effectively manage a center pivot irrigation system over the growing season. Where system capacity was adequate to meet crop water needs for a given soil and crop, the simulator maintained the soil water balance between field capacity and the minimum balance specified. During crop development periods when evaporative demand is high and rainfall is low, even high capacity systems

may not be able to prevent stress events. Increasing the pumping rate of the system often reduced the number of days below the minimum allowable balance.

A yield model was used to predict the relative yield in corn. The average relative yield for all pumping rates and soil types simulated was maintained at or above 90% for all sites except at Akron, CO. Average relative yields at Akron were lower mainly due to the inability of both a 37.9 and 50.5 L/s system to keep up with the ET demand. A 63.1 L/s system at this site was able to maintain relative yield above 90% on average for all the soil WHC's simulated.

Relative yield values increased when the DBM were decreased which indicated the minimum allowable soil water balance was set correctly. Although no yield model was used to analyze the soybean and potato simulations, it can be assumed that the software effectively managed irrigations indicated by the low number of DBM that occurred when system capacity was adequate enough to keep up with ET demand.

Actual field tests will need to be performed to determine any corrections or adjustments that may need to be made to the simulation software. Soil moisture readings may need to be implemented as a visual tool for the farmer and a means of correcting the actual soil water balance determined by the ET equation. The system should be developed for center pivots that do not travel a full revolution or irrigate multiple crops. The software also needs to incorporate multiple soil types within the same field. Also, all other variables that the farmer will be able to view and possibly change will need to be determined.

An alternative management strategy for irrigating potatoes should be explored. It may be possible to conserve additional water while maintaining yield if the target soil water balance is maintained at field capacity instead of attempting to keep it above the minimum allowable balance.

The Jensen-Haise equation appears to be a viable alternative to using the ASCE Penman Monteith equation to determine reference evapotranspiration in the upper Great Plains. This equation should be compared to the ASCE equation in other areas to determine to what extent using one method over the other affects the irrigator's bottom line. Implementing the Jensen-Haise method of predicting ET_r would reduce the installation cost and eliminate the uncertain reliability associated with the instruments used to measure wind speed and humidity.

Future research also is needed to document the impact of stress events upon predicted crop production.

The conclusions of this project were:

1. A crop specific irrigation scheduling software package was developed to relieve the producer of the daily tedium of scheduling irrigation.
2. Irrigation scheduling software was tested using a simulator for various crops, pumping rates, and soil water holding capacities with weather data collected at sites throughout the upper Great Plains.
3. The irrigation scheduling software was effective in preventing yield reduction for corn where system capacity was adequately sized to meet crop water needs.

4. Increased system pumping rate lowered the average number of days below the minimum allowable balance for a given soil type at a particular site.

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