Automated Water Management for Center Pivot Irrigation Systems

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Abstract

Simulations were conducted to determine the effectiveness of a software package that fully automates center pivot irrigation systems on fields planted to corn for years 1985-2004. A total of seven sites from the Central and Northern Plains were chosen for analysis (Akron, CO, Ames, IA, Brookings, SD, Sandyland, KS, Oakes, ND, Ord, NE, and Rock Port, MO). 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. A comprehensive analysis is presented in this paper for all sites for a pumping rate of 50.5 liters/second and an available water holding capacity of 125 mm/meter of soil. The average days under minimum allowable soil moisture capacity in a single growing season ranged from 37 at Akron, CO to one at Oakes, ND. Akron, CO also had the greatest average number of irrigation cycles in a growing season (24) with both Ames, IA and Oakes, ND having the least average number of irrigation cycles per season of sites analyzed with 12. The average ratio of actual evapotranspiration to water inputs for all sites was greatest at Sandyland, KS (0.95) and least at Oakes, ND (0.90).

Introduction

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. 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., 1994, 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. The practice of scientific irrigation scheduling is, however, seldom used by farmers. 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.

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.

The objective of this project was to create a software package to implement a water balance that relieves the producer of the daily tedium of scheduling irrigation.

Methods and Materials

The irrigation software calculated soil moisture balances and determined irrigation timing and depth of application for each six degree section on a full circle (360 degree) center pivot. The following parameters were held constant for all simulations:

Distance from center to furthest point reached by end gun = 418 m
Initial soil water content = 80% of field capacity
System application efficiency = 90%
Crop planted = Corn
Angles analyzed = 175-180

Scientific irrigation scheduling relies on the ability to accurately estimate evapotranspiration (ET). The FAO Penman Monteith (Allen et al., 1998) equation was chosen as the most reliable and accepted means of determining ET.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} \mu_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \tag{1}$$

ET_o - reference evapotranspiration [mm day^{-1}],
R_n - net radiation at the crop surface [MJ m^{-2} day^{-1}],
G - soil heat flux density [MJ m^{-2} day^{-1}],
T - mean daily air temperature at 2 m height [°C],
u_2 - wind speed at 2 m height [m s^{-1}],
e_s - saturation vapour pressure [kPa],
e_a - actual vapour pressure [kPa],
$(e_s - e_a)$ - saturation vapour pressure deficit [kPa],
Δ - slope vapour pressure curve [kPa °C^{-1}],
γ- psychrometric constant [kPa °C^{-1}].

Required weather data were collected and recorded at automatic weather stations for each of the simulated sites and downloaded from the High Plains Regional Climate Center online databases. The reference evapotranspiration (ET_0) value was calculated for each day past a given planting date (Table 1).

Table 1. 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
Sandyland, KS	April 1	180
Oakes, ND	May 1	150
Ord, NE	April 1	180
Rockport, MO	April 1	180

ET_0 was multiplied by a crop coefficient and a plant available water coefficient (Equation 2). The crop coefficient was adapted from FAO coefficients (Allen et al., 1998) to fit the growing season length for each chosen site.

$$ET_c = ET_o * K_c * K_a \qquad (2)$$

Et_c – actual evapotranspiration (mm)
ET_o – reference evapotranspiration (mm)
K_c – crop coefficient
K_a – plant available water coefficient

The plant available water coefficient decreases as the amount of available water in the soil decreases (Jensen et al., 1990).

$$K_a = \frac{\ln(AW + 1)}{\ln(101)} \qquad (3)$$

K_a – plant available water coefficient
AW – available water (%)

Initial rooting depth of the corn crop was set to 0.3 m to provide a buffer at the beginning of the season and was gradually increased to a maximum depth of 0.9 m when the crop reached maximum height above the soil surface. Minimum soil moisture levels were set to 30% of field capacity in the initial growing stage, increased from 30% to 60% during the developmental stage, maintained at 60% of field capacity during midseason, and decreased from 60% to 35% in late season.

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 maximum application depth value was set to 60% of field capacity in the initial growing stage, increased from 60% to 80% during the developmental stage, maintained at 80% of field capacity during midseason, and decreased from 80% to 50% in late season. The maximum depth of water that could be applied at one time was set at 32 mm with a minimum depth set to 13 mm.

ET forecasting was used to determine the timing and depth of irrigation applications. The predicted four day future ET total was found by taking the average of the previous two days ET and projecting it for the next four days. This predicted four day ET total was then subtracted from the current soil moisture balance for each six degree section of the pivot. If this predicted balance fell below the minimum allowable soil moisture, that individual section of the field was determined to be in need of irrigation at that future time. 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.

Daily rainfall was added to the soil moisture balance. If the soil moisture 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 an additional day. The only exception to this rule was when the ET for the additional 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.

To analyze the effectiveness of the simulation software, an ET ratio (water balance ratio) was calculated for each simulation.

$$ETratio = \frac{ET_c}{(R + I - Ex + Ex_I)} \quad (4)$$

ETratio - ratio of evapotranspiration to soil moisture inputs
ET_c – actual evapotranspiration (mm)
R – rainfall (mm)
I – irrigation (mm)
Ex – amount above field capacity (mm)
Ex_I - amount above field capacity caused by an irrigation event (mm)

All variables in the ratio are seasonal totals. The amount above field capacity (*Ex*) is calculated on a daily basis by subtracting the field capacity value from the actual balance. The amount above field capacity caused by an irrigation event (Ex_I) is any amount above field capacity that takes place up to four days after an irrigation event in any given section of the field. This ratio was developed to determine if the software was able to schedule irrigation events to meet the soil moisture losses incurred by evapotranspiration. A ratio of one indicates that all ET losses were replenished by rainfall and irrigation. The overall effectiveness of the software package was determined by finding the ET ratio and number of days that the section of the field being analyzed was under the minimum allowable water content.

Simulation software to fully automate the center pivot irrigator was written in ***National Instruments Labview Version 7.1***.

Results

A comprehensive analysis was completed on all sites with the variables of pumping rate and soil available water holding capacity held constant at 50.5 L/s and 125 mm/m of soil, respectively (Table 2). The goal of the project was to analyze sites for the years 1985-2004. However, downloadable weather data were not available for all years at all locations.

Table 2. Summary of results for the seven locations with a pumping capacity of 50.5 L/s and water holding capacity of 125 mm/m.

	Total ET (mm)	Rainfall (mm)	Irrigation (mm)	Excess Water (mm)	Excess Caused By Irrigation (mm)	ET Ratio	Days Under Minimum Allowable	Irrigation Cycles
Akron, CO	961	340	729	87	37	0.94	37	24
Ames, IA*	694	647	346	305	80	0.92	3	12
Brookings, SD	641	406	397	133	32	0.92	4	13
Oakes, ND**	576	354	355	102	31	0.90	1	12
Ord, NE	765	442	474	131	39	0.93	9	16
Rock Port, MO***	716	574	399	253	53	0.93	4	14
Sandyland, KS	913	436	630	145	42	0.95	26	21

* average values for 1986-2004
**average values for 1990-2004
***average values for 1991-2004

The ratio of average rainfall to average ET for the season was least at the Akron, CO site (0.35). This low ratio indicates a greater need for irrigation to replenish the losses from ET resulting in an average seasonal irrigation of 729 mm. The highest ratio for the sites analyzed was at Ames, IA (0.93) which triggered the lowest average seasonal irrigation depth of 355 mm.

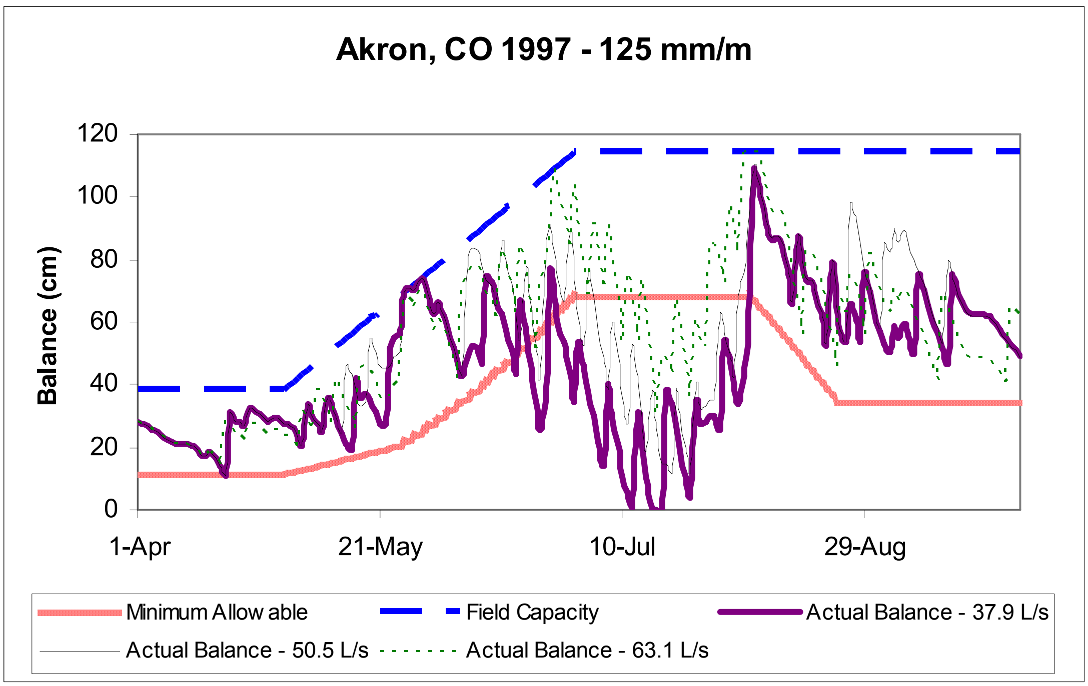

Figure 1. Soil water content for three pumping capacities at Akron, CO in 1997.

Akron, CO averaged the greatest number of days under the minimum allowable soil moisture (37) despite the system completing an average of 24 irrigation cycles per season. This is an indicator that the system pumping capacity is not adequate enough to meet the ET needs of a corn crop with this soil moisture capacity located in this particular climate. Even the higher pumping rate of 63.1 L/s was unable to maintain soil water content greater than minimum allowable at Akron (Figure 1). The total calculated ET for this growing season was 930 mm with a seasonal rainfall of 292 mm. The days under minimum allowable water content dropped from an estimated total of 45 days at a pumping capacity of 37.9 L/s to 18 days at 63.1 L/s.

At the simulated pumping capacity of 50.5 L/s and available soil moisture of 125 mm/m of soil, the Oakes, ND site only had only four years (1991 ,1992, 2001, 2002) that had any days during the growing season in which the actual soil balance dropped below the minimum allowable balance. In 1997 at Oakes, all system pumping capacities simulated were able to keep up with the ET demand (Figure 2).

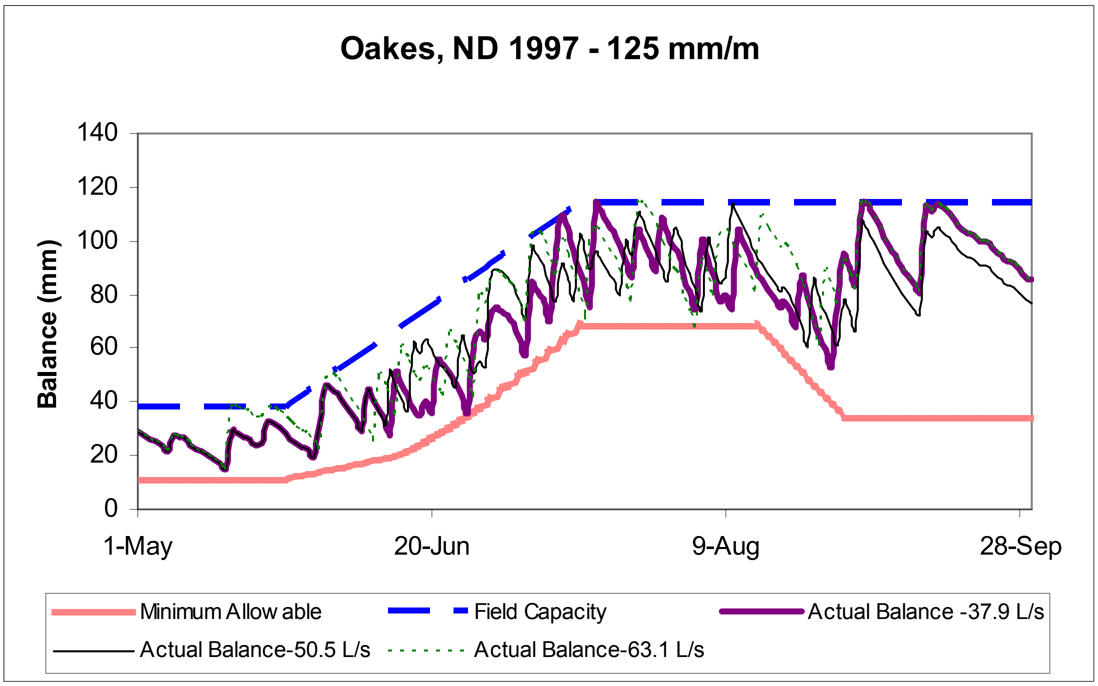

Figure 2. Soil water content for three pumping capacities at Oakes, ND in 1997.

At some of the sites, excessive water inputs lowered the ET ratio values. Though they may appear as a result of irrigation, most are caused by ill-timed or excessive rainfall. Quite frequently, the reason for the apparent excess water is caused by rainfall occurring during non-critical stages of crop development both early and late in the growing season.

In 1989 at Ames, IA, the wettest growing season in this study, there was a total of 1166 mm of rain (Figure 3). This total is over 500 mm greater than the average seasonal rainfall of 648 mm for the years analyzed. These rainfall events, which were often large early in the growing season, contributed 638 mm of the 826 total mm of excess water. The total rainfall for the season was much greater than the ET losses (648 mm). Since much of the rainfall occurred before the critical growing stage for corn, the simulation software instructed the pivot to apply 272 mm of water to overcome deficits during critical growth stages in July and August when rainfall was deficient.

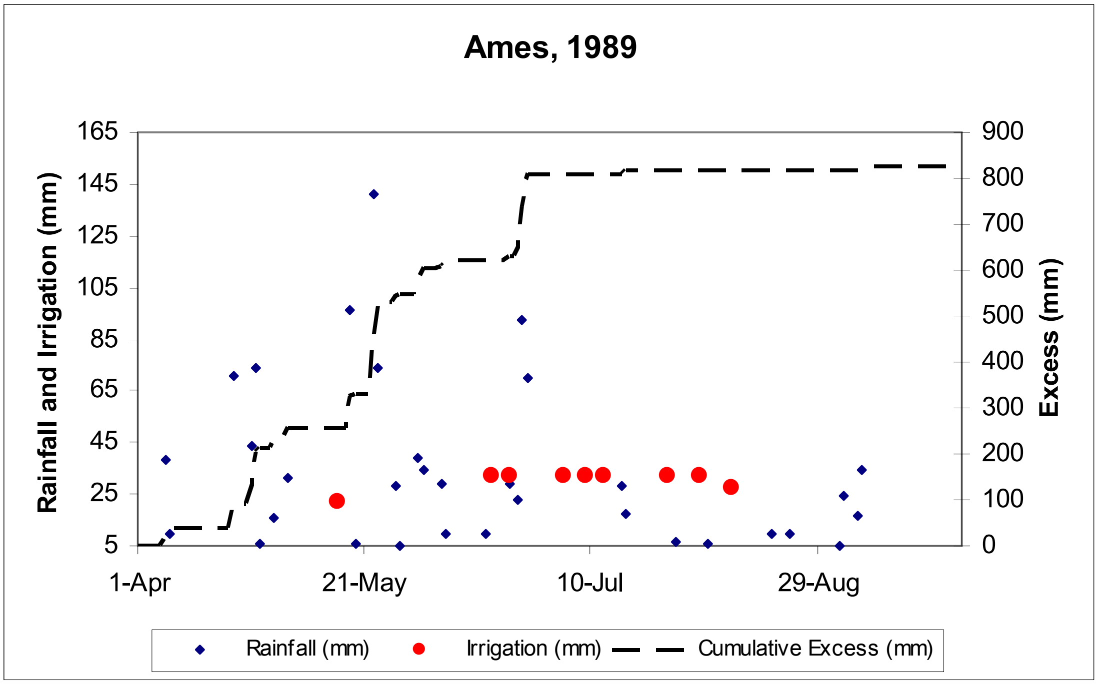

Figure 3. Timing of rainfall and irrigation events in relation to the overall excess moisture above field capacity at Ames, IA in 1989.

Discussion

Simulation software was developed to perform irrigation scheduling using 20 years of weather data for seven locations in the Upper Great Plains where center pivots are the dominant method of irrigation. Simulations were conducted for three system capacities and three soil moisture holding capacities. ET was estimated for corn using the FAO Penman-Monteith method. 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, the simulator maintained the soil water balance between field capacity and the minimum balance specified. Even though a buffer was included in the model to allow for rainfall storage, unplanned rainfall events often exceeded field capacity of the soil. 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.

Actual field tests will need to be performed to determine any corrections or adjustments that may need to be made to the simulation software. Future research is needed to document the impact of stress events upon predicted crop production.

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