TECHNICAL SESSION PROCEEDINGS

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Table of Contents

Agricultural

Turf

Water Management

Crop Yield Predictor for Deficit Irrigation Scheduling

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ABSTRACT

Many irrigators face the prospect that they will not be able to fully irrigate their crops. They still need to schedule their water applications to make the best economic use of available water. Major scheduling questions for deficit irrigation include: will pre-season irrigation be beneficial, and when should irrigation be initiated and terminated during the growing season. A computerized decision tool, the Crop Yield Predictor (CYP) has been developed to predict yields from alternative irrigation schedules. The user determines soil water status before or during the cropping season and formulates a potential schedule of irrigation dates and amounts. CYP uses a daily soil water balance coupled with computations of effective evapotranspiration (ETe) to predict crop yields from regional yield-ET relationships. Multiple executions of CYP with alternative irrigation schedules lead to the schedules that project optimum net economic returns from the management scenarios.

INTRODUCTION

Maximum net economic returns for irrigators with adequate water supplies usually have corresponded to irrigation management that is geared to obtain maximum crop yields. Irrigation in excess of crop water needs reduces net economic return, but the marginal increases in crop yields, especially for corn, usually are more than marginal production costs. When water supplies cannot match crop needs and deficit irrigation management is anticipated, optimum net economic return from irrigation is the appropriate measure of best management (English 2002). Crop selection for optimum net return may involve multiple crops in rotation, a single crop with reduced irrigation, or irrigation on a smaller area (Martin et al. 1989). In addition to crop selections, irrigation needs to be allocated among crops, using crop production functions and production costs for optimum economic return (English, 1981, Klocke et al. 2006).

When the water supply for irrigation is less than the water required for non-stressed crops, water deficits can be anticipated. Irrigation schedules for deficit irrigation need to anticipate the potential crop yields and net economic returns prior to and during the growing season. The major irrigation scheduling decisions for deficit irrigation are: (1) whether or not pre-season irrigation is needed (Stone et al., 2008), (2) when should the first irrigation event start, and (3) when should the last irrigation event be applied. Between the start date and stop date, irrigation systems often operate on a fixed frequency depending on the water supplied by surface or ground water.

The objective for this study was (1) to develop an interactive decision tool that would help users predict optimum irrigation schedules for crops that are expected to experience water stress and (2) to illustrate the use of the decision tool to predict irrigation schedules for a range of annual precipitation, application amounts, and preseason irrigation.

CROP YIELD PREDICTOR DESCRIPTION AND OPERATION

The CYP was designed as an interactive decision tool to predict crop yields and economic returns for deficit irrigated crops. CYP uses the Kansas Water Budget (KSWB) simulation model to predict crop yields, reference ET (ETr), effective ET (ETe), crop yields, and daily available soil water (ASW) (Stone et al., 1995; Stone and Schlegel, 2006; Khan et al., 1996; Klocke et al., 2009). The KSWB is designed to use average daily values from 30 years of weather data (maximum and minimum air temperature, solar radiation, and precipitation) for each location to calculate ETr, ETc, daily ASW, and crop yields. CYP users can designate potential irrigation schedules to optimize yields and net returns. These schedules can be tested for a range of annual precipitation to find yield and income risks from several input scenarios including wet, average, and dry years; different dates and amounts of irrigation events; inclusion or exclusion of pre-season irrigation (Stone et al., 1987); different soil types; different irrigation system application efficiencies; or different soil water contents before or during the growing season.

User Inputs

The CYP is structured with a series of tabs and sub-tabs that activate screens for input and output information (figure 1). The first level of tabs is for “general input” and “results”. The general input tab activates a series of sub-tabs including “location and rainfall”, “soil information”, “irrigation efficiency”, “crop selection and irrigation schedule” and “runoff and soil water” that require the user to enter the information needed to execute the program.

The **“location and rainfall”** tab shows the screen for choosing the nearest location to the user’s field and the desired annual rainfall. Annual rainfall can be entered manually or by clicking onto the average value for the location or the amounts based on probability of occurrence. Probabilities indicate the rainfall amounts that occur during 8 out of 10 years (80%), 5 out of ten years (50%), or 2 out of 10 years (20%). Each day’s rainfall is adjusted up or down with the ratio of the user’s annual precipitation and the average annual precipitation from weather records.

The **“soil information”** tab shows a screen with four soil types, including medium and coarse textured soils that can be highlighted by the user for the predominant soil type in the field. Soil water characteristics, including available soil water (ASW) storage capacity, field capacity, and permanent wilting for each soil are displayed so the user can choose the one that is closest to their field soil type. Soil type influences the default runoff coefficient, which is the percentage of daily precipitation that does not infiltrate into the soil.

The **“irrigation efficiency”** tab displays suggested irrigation application efficiencies by system types. Application efficiency is defined as the percentage of water that infiltrates into the soil (net irrigation) from the water pumped or supplied to the field (gross irrigation). The user needs to enter irrigation efficiency manually from values in the table or enter the desired efficiency.

The **“crop selection and irrigation schedule”** tab activates two sub-tabs, one for selecting a crop and one for building an irrigation schedule for that crop. The crop selection sub-tab allows the user to highlight a crop from a list which includes corn, grain sorghum, wheat, soybean, sunflower and alfalfa. CYP fills a default growth stage table for the chosen crop, but the user can adjust these dates from field observations. The user also fills a “maximum yield” box for the field’s non-stressed yield potential. This yield is based on the field’s history of non-stressed production and a reasonable expectation for yield increases from better cropping practices or technology improvements. CYP simulates a crop yield for a given input scenario and the maximum yield for a non-stressed crop. A ratio of predicted yield, calculated from the inputs, and maximum non-stressed yield produces a relative yield. The relative yield is multiplied by the user’s maximum field yield to produce a field based crop yield.

The **“irrigation schedule”** sub-tab allows the user to select one of two sub-sub tabs. The “gross irrigation entries” tab prompts the user to build a customized irrigation schedule by entering specific dates and gross irrigation amounts applied on that date. The irrigation dates can be entered manually or imported from schedules that are developed in Excel.

An alternative to building a customized schedule is for the user to choose the sub-sub tab for “uniform frequency of irrigation events”. This option determines irrigation schedules based on the same number of days between irrigation events from user entries of (1) starting dates and ending dates for the growing season irrigation, (2) gross irrigation for each irrigation event, where the gross irrigation was the same for all irrigation events, and (4) area irrigated. The user then needs to determine whether the irrigation schedule needs to be based on pumping capacity or the amount of total irrigation for the season. When pumping capacity is the limiting factor, CYP calculates the number of the irrigation events that are possible between the starting date and ending dates for the entire irrigation season and enters those irrigation events into the irrigation schedule. When the total irrigation amount controls the schedule, all of the water is applied with a uniform frequency without regard to the pumping capacity. The uniform frequency schedules can be modified after they are entered into the scheduling table.

The **“runoff and soil water”** tab sets the runoff coefficient, ASW on January 1, and any ASW updates after January 1. The runoff coefficient is the percentage of daily precipitation that does not infiltrate. The user manually enters the runoff percentage or CYP calculates a default runoff factor using crop type, total annual precipitation, and soil type.

CYP calculates available soil water (ASW) on January 1 from annual precipitation and anticipated irrigation, but this value can be modified by clicking onto the ASW input box. The user can modify the ASW on any date during the year except January 1 by checking the “Use ASW and Date values below” box. The value of ASW is entered into the input box and the calendar drop down gives the choice of a date.

CYP Outputs

Results of a simulation are tabulated and presented in graphs of daily available soil water, crop ET, and drainage. Results from additional scenarios can be retained in additional columns on the results table.

Evaporation during the non-growing season is calculated for water loss from bare soil. A daily evaporation coefficient (Doorenbos and Pruitt, 1977) is multiplied by ETr to calculate evaporation.

Effective crop evapotranspiration (ETe) is the water that contributes to crop yield. ETe is calculated in four steps. First, long-term average daily weather data, including maximum temperature, minimum temperature, and solar radiation, were derived from at least thirty years of records at each geographic location. Theses average daily weather data combine for a calculation of reference ET (ETr) with the method described by Jensen and Haise (1963) for a well-watered crop with full canopy cover in semi-arid regions. When the maximum air temperature is more than 33°C, ETr is adjusted to account for additional advective energy. Second, daily ETr is multiplied by a crop coefficient (Kc) to produce a value for maximum ET (ETm) that accounts for increasing ETm during vegetative growth, nearly constant ETm during reproduction and early grain fill, and declining ETm as the crop matures. Adjusting growth stage dates allows CYP to recalculate daily crop coefficients (Kc) for the duration of the growing season (figure 2). Calculation of ETm assumes that the crop is not experiencing water stress and there are no "spikes" in soil water evaporation immediately after surface wetting because the Kc values were developed to account for surface evaporation. Third, ETm is multiplied by a soil water stress coefficient (Ks) (Jensen et al., 1971) producing an actual crop ET (ETa), which is the water extracted from the soil and accounts for the effect of soil water depletion on the ETm (figure 3). Finally, ETa is reduced to account for the crop's susceptibility to water stress to stress during four growth periods (vegetative, flowering, seed formation, and ripening) to produce ETe. The ratio of ETa to ETm and water stress factors by crop and growth periods convert ETa to ETe. These four steps combine the effects of weather parameters, crop development during the growing season, the amount of water stress from soil water availability, and the crop's susceptibility to stress during four growth periods. Klocke et al. (2009) described the derivation of ETr, ETm, ETa, and ETe in more detail.

Maximum crop yield (Ym) is calculated from linear relationships of crop yield and maximum ET (ETm) where the crop is not experiencing stress due to soil water or the crop's susceptibility of the crop to stress during different growth stages.

Estimated crop yields (Ye) are calculated by from linear relationships of yield as a function of effective ET (ETe), developed from long-term field studies in west-central Kansas:

Yield [Mg ha^{-1}] = 0.042 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 12.33 [Mg ha^{-1}] for corn,
Yield [Mg ha^{-1}] = 0.030 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 5.67 [Mg ha^{-1}] for sorghum,
Yield [Mg ha^{-1}] = 0.015 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 4.04 [Mg ha^{-1}] for wheat,
Yield [Mg ha^{-1}] = 0.10 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 1.3 [Mg ha^{-1}] for sunflower,
Yield [Mg ha^{-1}] = 0.011 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 2.39 [Mg ha^{-1}]] for soybean,

where ETe is the water that actually contributes to crop yield.

Relative crop yield is the ratio of the crop yield (Ye), calculated by CYP, and the non-stressed yield (Ym). Relative yield is what was actually produced as a percentage of the yield that would have been produced with no water stress.

Adjusted crop yield is the relative yield multiplied by the program user's maximum field yield provided by the user. The CYP calculates relative yield, but the adjusted crop yield is a better indicator of the expected field yields from the simulated scenario.

Net return is the gross income minus operational and irrigation costs. Net return is income before fixed costs are considered. For deficit irrigation, net return is a better indicator of the optimum irrigation scheduling scenario than considering only crop yield results

Drainage during the growing and non-growing seasons is calculated using a Wilcox-type drainage equation (Miller and Aarstad, 1972) that was field calibrated for each soil type. Drainage depends on the relationship of total soil water described by an exponential function relating drainage to total soil water.

The **"graph"** tab accesses three graphs for the current simulation including (1) daily ASW throughout the year, (2) ETr, ETm, and ETa (figure 3) , and (3) drainage, each on a daily basis throughout the year. The ASW on December 31 can be entered manually for next year's simulation if the user wants to add the same crop or other crops in subsequent years.

Daily available soil water (ASW) is graphed by CYP from a soil water balance of:

$$ASW_t = ASW_y + P_y + I_y - D_y - ETa_y$$

where ASW_t is the available soil water at the beginning of today; ASW_y is the available soil water at the beginning of yesterday; P_y is the precipitation that infiltrated into the soil yesterday, I_y is the irrigation that infiltrated into the soil yesterday; D_y is the water that drained from the six foot depth in the soil yesterday; and ETa_y is the water that the crop consumed yesterday (figure 3).

EXAMPLES OF CYP SIMULATIONS

CYP was executed with the input values in table 1. The simulations were designed to show the effects of annual precipitation probabilities, growing season irrigation amounts, and pre-season irrigation on ETe, crop yield, income, and net return.

Annual precipitation probabilities (20 to 80%) were chosen to represent the range of precipitation to evaluate the resulting range of ETe and yields. ETe from the 20% and 80% precipitation was ± 5% of the ETe from the 50% precipitation probability, while yield expectations were ± 9% of the 50% precipitation probability (table 2). Operational and pumping costs were calculated for the 50% rainfall probability and applied to all precipitation probabilities because input costs would be spent in without knowledge of future precipitation. Net return for the 80% and 20% precipitation probabilities were from -60% to + 25% of the net return for the 50% precipitation probability. Annual precipitation had a strong influence on net return.

CYP users can compare anticipated irrigation amounts to find the potential range in crop yields and net returns (table 3). Growing season irrigation amounts were ± 20% of 254 mm. Irrigation events commenced earlier and ceased later with the additional irrigation events because the capacity for delivering water to the field limited the irrigation frequency. Over the range or irrigation, ETe was ± 2% and yield was ± 8% of the 254 mm growing season irrigation. Growing season irrigation of 203 mm had a net return that was 14% more than the 254 mm irrigation and 5% less net return for the 305 mm irrigation. Operational costs, including fertilizer, seed, and harvesting, were scaled with the yield expectations for the amount of irrigation. Even though more net return resulted from the least irrigation, income variability would increase from year to year with less irrigation (Klocke et al., 2009b). The CYP considered average results over years rather than possible results for individual years.

The value of pre-season irrigation is an issue when non-growing season precipitation is less than average and irrigators perceive that they will not be able to keep up with ET requirements later in the growing season (Stone et all, 2008). Often precipitation during April, May, and early June occurs in the Great Plains region that is not anticipated during March when irrigators usually make pre-season irrigation decisions. The CYP can be used to forecast the advantage of pre-season irrigation to impact potential crop yields and net returns (table 4). In this example, either 53 or 102 mm of pre-season irrigation was applied in late March and early April on corn in 2 or 4 irrigation events. ETe was 3% and 5% more for 53 and 102 mm pre-season irrigation compared with no pre-season irrigation. Likewise, yields 10% and 20% more for 53 and 102 mm of pre-season irrigation compared with no pre-season irrigation. However, net returns were 17% and 28% less for 53 and 102 mm of pre-season irrigation compared with no pre-season irrigation. Projected operational costs and pumping costs did not compensate for the added crop yield for pre-season irrigation.

SUMMARY

The Crop Yield Predictor (CYP) has been adapted from the Kansas Water Budget (KSWB) to become an interactive model where the user can enter a western Kansas location. Annual precipitation, soil type, crop type, a potential irrigation schedule, runoff, initial soil water (SW) content, crop production costs, and commodity prices are inputs to the CYP. These inputs combine to predict effective ET, grain yield, relative grain yield, daily SW content, daily drainage, daily crop ET, and net economic returns. Alternative irrigation schedules and annual precipitation can be entered into CYP to predict changes in results. The alternative schedules can guide CYP users in choosing irrigation starting dates ending dates and irrigation frequencies.

Multiple executions of the CYP illustrated that: (1) increases in annual precipitation, from 380 to 584 mm, had a positive impacts on crop yields and positive impacts on net economic returns; (2) increases in growing season irrigation, from 203 to 305 mm, had positive impacts on crop yields but a negative impacts on net returns; (3) pre-season irrigation, from 0 to 103 mm, had positive impacts on crop yields but negative impacts on net returns.

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Table 1. Input values for scenarios in tables 3, 4, and 5.

Location	Garden City
Crop	Corn
Soil Type	Ulysses Silt Loam
Runoff	5%
Application Efficiency	90%
Gross Irrigation	25 mm per event
Crop Price	\$165 Mg^{-1}
Irrigation Costs	\$0.14 ha^{-1} mm^{-1}

Table 2. Effects of the amount of annual precipitation with Probabilities of 80, 50, and 20% with growing season irrigation equal to 254 mm and 45% ASW at the beginning of the year.

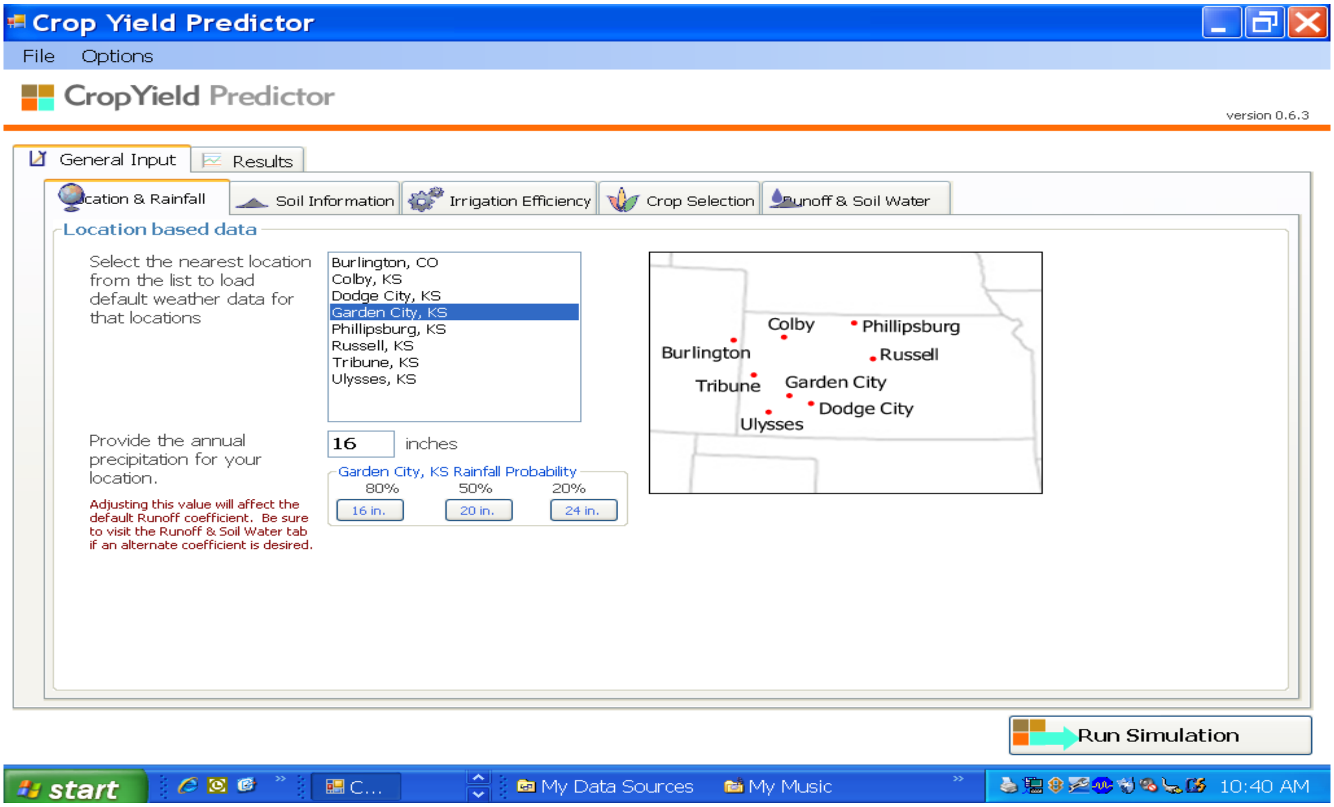
	Annual Precipitation (mm)		
	380	483	584
Effective ET (mm)	533	559	584
Yield (Mg ha^{-1})	10.0	11.5	12.5
Gross Income (\$ ha^{-1})	1647	1901	2056
Operational Costs (\$ ha^{-1})	1040	1040	1040
Pumping Cost (\$ ha^{-1})	233	233	233
Net Return (\$ ha^{-1})	374	628	783

Table 3. Effects of growing season irrigation with annual precipitation equal to 483 mm and 45% ASW at the beginning of the year.

	-Gross Irrigation (mm)-----		
	203	254	305
Effective ET (mm)	533	546	559
Yield (Mg ha^{-1})	10.9	11.9	12.9
Gross Income (\$ ha^{-1})	1791	1957	2123
Operational Costs (\$ ha^{-1})	859	1074	1233
Pumping Cost (\$ ha^{-1})	188	233	275
Net Return (\$ ha^{-1})	744	650	615

Table 4. Effects of pre-season irrigation for growing season irrigation equal to 203, annual precipitation equal to 483 mm, and 25% ASW at the beginning of the year.

	Pre-season Irrigation (mm)		
	0	53	102
Effective ET (mm)	508	521	533
Yield (Mg ha^{-1})	9.8	10.9	11.7
Gross Income (\$ ha^{-1})	1625	1791	1924
Operational Costs (\$ ha^{-1})	859	1074	1233
Pumping Cost (\$ ha^{-1})	188	233	275
Net Return (\$ ha^{-1})	578	484	416



Location based data

Select the nearest location from the list to load default weather data for that locations

Burlington, CO
Colby, KS
Dodge City, KS
Garden City, KS
Phillipsburg, KS
Russell, KS
Tribune, KS
Ulysses, KS

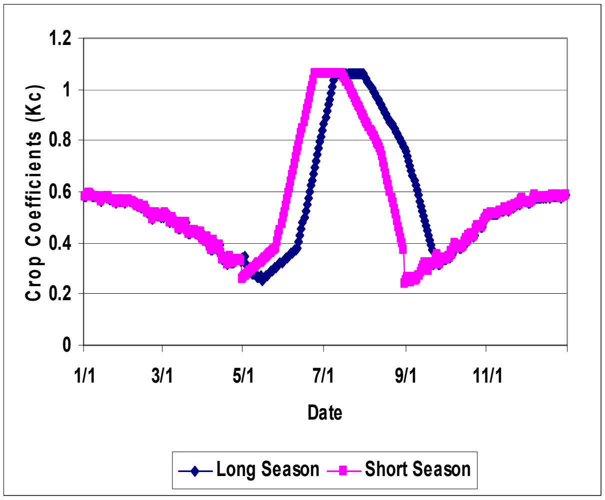
Provide the annual precipitation for your location. 16 inches

Adjusting this value will affect the default Runoff coefficient. Be sure to visit the Runoff & Soil Water tab if an alternate coefficient is desired.

Garden City, KS Rainfall Probability

80%	50%	20%
16 in.	20 in.	24 in.

Figure 1. Example of input screen for the Crop Yield Predictor.



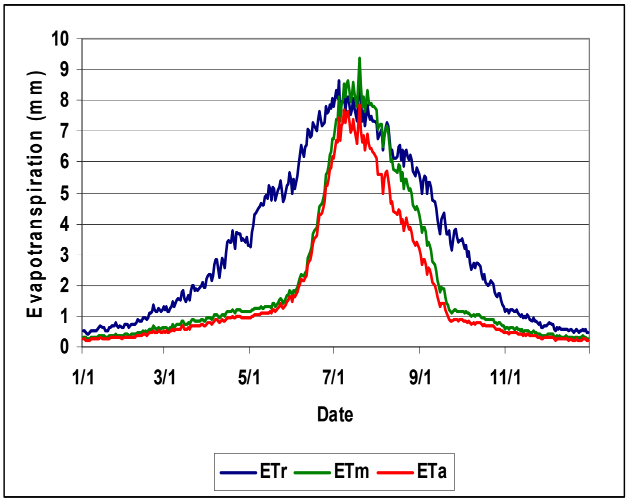


Figure 2. Example of Kc for short season corn planted early and long season corn planted later.

Figure 3. Example of ETr, ETm, and ETa

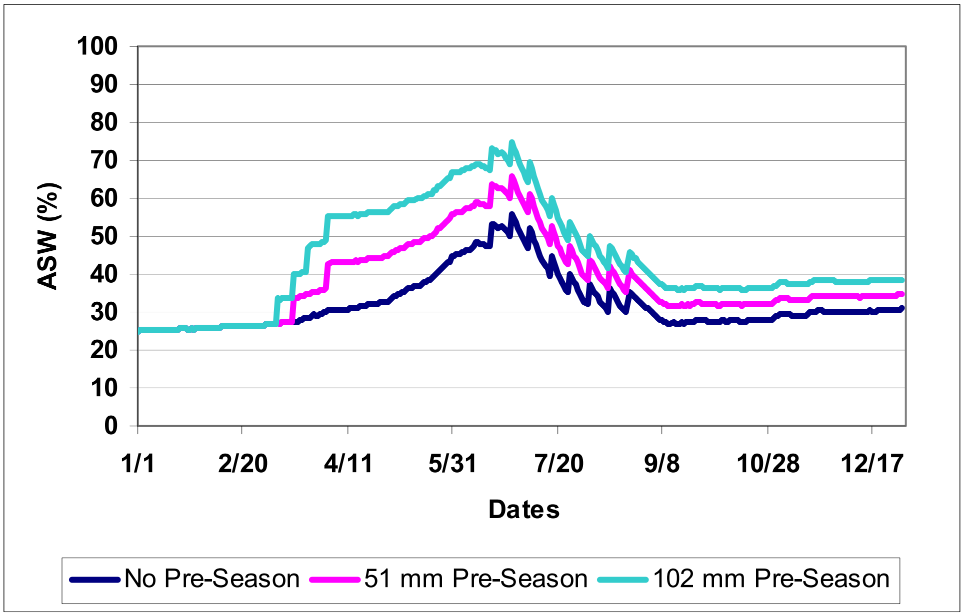


Figure 3. An example of available soil water (ASW) graph for the year with and without pre-growing season irrigation.

Simple Charts for Modifying Crop Coefficients to Local Conditions

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Abstract. The d*efault crop coefficient values used in FAO-56 were developed for sub-humid climatic conditions with an average daily wind speed of 4 ½ mph (2 m/s) and an average daily minimum humidity of 45%. However, coefficient values can be modified with mathematical procedures to compensate for differing climatic conditions. Not modifying default values to local climatic conditions could cause over- or under-irrigation to occur. This paper presents a simplified method to modify crop coefficient values using look-up tables for approximately 180 locales in the USA and its possessions and Algiers City, Algeria. The tables are based on long-term climatic data available from the NOAA. The coefficient value that deviates the most from FAO-56 default values is the* ***K-c_ini*** *value, which sometimes needs to be increased 200%. This deviation occurs when high numbers of rainfall/irrigation events occur. Since rainfall on two or more consecutive days is considered one rainfall "event", a mathematical estimate was developed to convert total number of days with >0.01 inch or more rainfall per month to the number of non-contiguous rainfall events.*

Keywords. Crop coefficients, irrigation scheduling, FAO-56.

Introduction

This paper is based on procedures to adjust the default crop coefficient (K_c) values that are provided in *FAO-56, Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56* (Allen et al., 1998). Adjustment of K_c values allows one to modify default FAO-56 K_c values to allow them to more accurately conform to local climatological conditions.

Crop coefficient value (K_c) is used in the following way to predict water use:

$$ET_c = ET_o \times K_c \qquad \text{Eq. 1}$$

Where, ET_c is the water use of the crop in question (inches or mm)
ET_o is reference evapotranspiration (inches or mm)

The FAO-56 procedure is very Spartan in concept and involves just three K_c values to describe conditions for the entire growing season; these points are: **K_{c_ini}**, **$K_{c\text{-}mid}$**, and **$K_{c\text{-}end}$**. However, based on local climate conditions, these default values can be increased or decreased (referred to as VERTICAL adjustment). A curve is then constructed through the three points to encompass the whole growing season and is known as the *crop coefficient curve*. The horizontal placement of the **K_{c_ini}**, **$K_{c\text{-}mid}$**, and **$K_{c\text{-}end}$** values is based on the length in days of four crop development periods: *Initial*, *Crop development, Mid-season*, and *Late-season*.[1] Figure 1 shows the four-period, three-coefficient approach of building a crop coefficient curve.

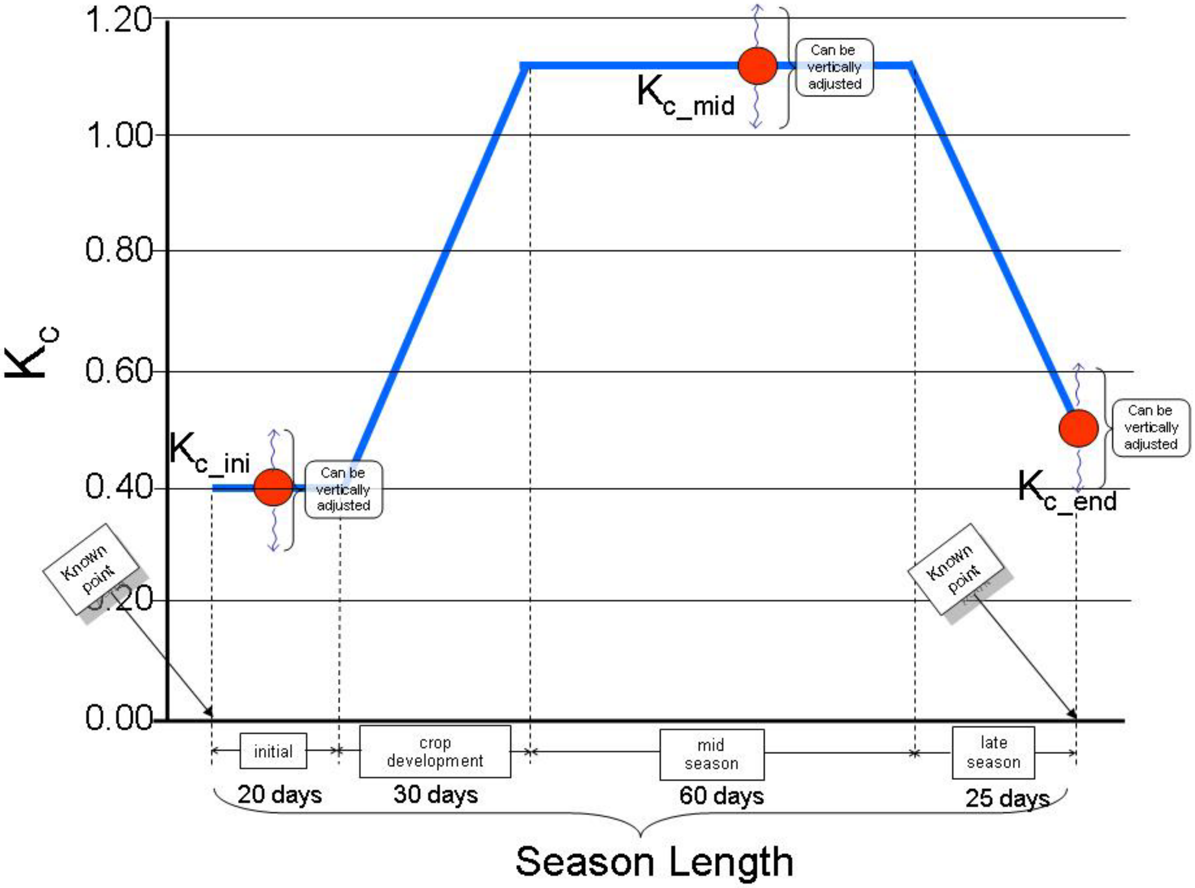

Figure 1 A constructed crop coefficient (Kc) curve for soybeans planted in central USA in May (after Allen et al., 1998). The three default Kc values can be modified to better meet local climatic conditions.

Crop Coefficients

The crop coefficient is the keystone to accurately predict crop water use from weather data. Crop water use, ET_c, is determined by adjusting the known value of ET_o with the proper crop coefficient value (K_c). Sometimes, $ET_c > ET_o$, which indicates that the crop in question uses

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[1] Adjusting the amount of time for any of these periods results in HORIZONTAL adjustment, but is not the topic of this paper. However, it is an important consideration. For example, the Initial period goes from planting to 10% ground cover. It is obvious that soybeans planted in 38-inch rows in April and those drilled in rows 7 ½ wide in mid-June will reach 10% cover at greatly divergent times.

more water than does the reference crop, thus the crop coefficient >1.0. When $ET_c < ET_o$, the crop coefficient value < 1.0.

In consumptive use research the studied crop's rate of water use, ET_c, is empirically determined (through lysimeters, Bowen ratio equipment, neutron probes, etc.), after which crop coefficient values are then developed by rearranging Eq. 1 to the form of Eq. 2, which is valid for periods that have not received rainfall or irrigation.

$$K_c = ET_c \div ET_o \qquad \text{Eq. 2}$$

Over the growing season, crop coefficient values for a season start out low, increase as the canopy fills in, and then plateaus out until they begin to decline with the unsought of crop senescence. When plotted over the season, the changing crop coefficient values have the shape of an upside-down sauce pan. K_c values plotted over time are referred to as a crop coefficient curve or Kc curve. The actual day-to-day K_c values along the K_c curve exhibit much bounce as seen in Figure 2 (after Howell, 1998).

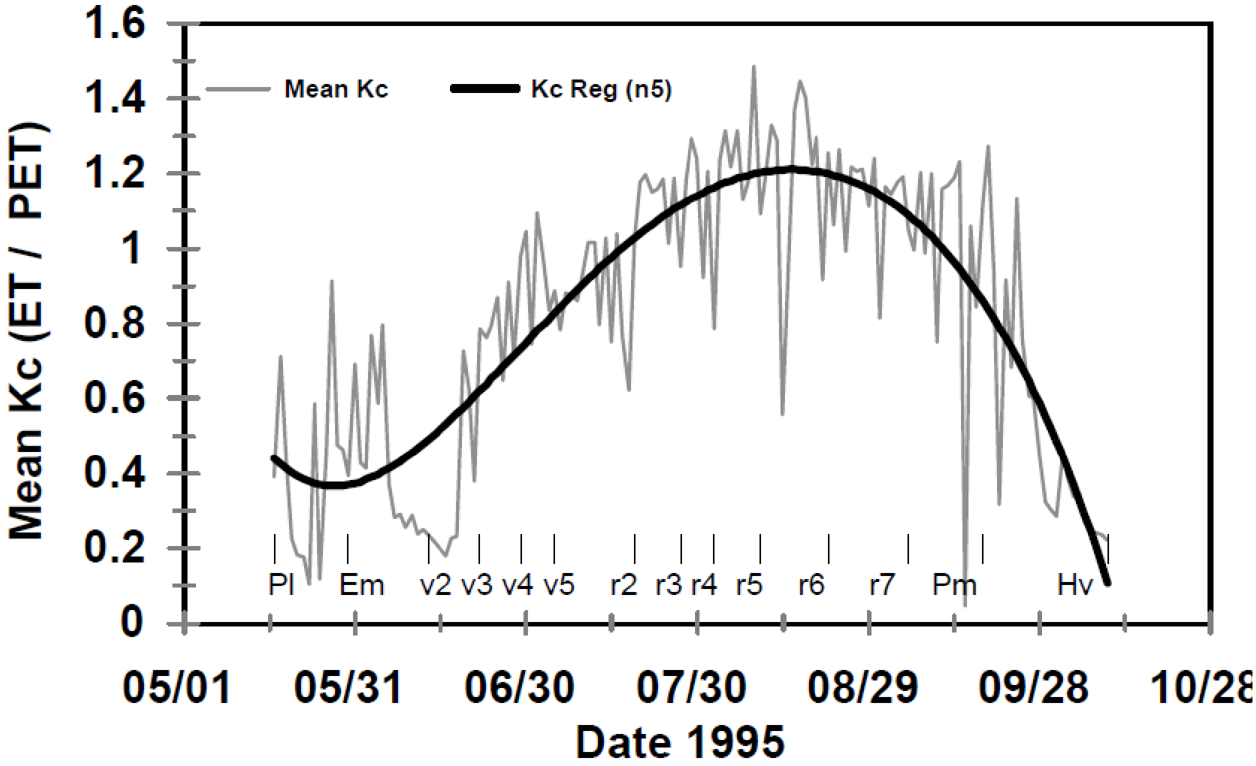

Figure 2 Actual crop coefficient values determined by a weighing lysimeters for soybeans and the best fit curve (i.e., crop coefficient curve) for the same data (after Howell, 1998).

Crop coefficients are of two types. The most commonly used one is the *single crop coefficient* (K_c). This coefficient is used when crop transpiration (T) and soil evaporation (E) are combined jointly. The *dual crop coefficient* (K_{cb} +K_e) is used when T and E are calculated separately; it is also referred to as the *basal crop coefficient*. The single crop coefficient value will be higher since it has to account for water loss through both T and E. The normal range of K_c values is from 0.30 to 1.20, whereas, the normal range of K_{cb} values is from 0.15 to 1.15.[2]

Modifying Default Crop Coefficient Values

Suggested values for both types of coefficients are provided in FAO-56. The mid- and end-season coefficient values (K_{c_mid} and K_{c_end}) were derived from locations having an average daily minimum Relative Humidity value of 45% and an average daily wind speed of 4 ½ mph (2 m/s). Additionally, crop height also influences values.

The initial crop coefficient value (K_{c_ini}) is influenced by ET_o, frequency between wetting events, and soil type/depth of wetting event. The initial crop coefficient values appear to be based on locales having an average early season daily ET_o of 0.15 inches (4 mm) per day and about a 10-day frequency between wetting events. Table 1 shows the various factors that influence adjustment for the three cardinal coefficient values for both types of crop coefficients.

Table 1. Factors used in adjusting crop coefficient values.

Type of coefficient	Period Coefficient		
	Kc_ini	Kc_mid	Kc_end
Single crop coefficient (K_c)	~ ETo ~ frequency of wetting ~ wetting depth ~ soil type	~ crop height ~ min. RH ~ wind ~ freq. of wetting (only if K_{c_mid} <1.0)	~ crop height ~ min. RH ~ wind ~ desired harvest conditions ~ don't adjust if K_{c_end} <0.45
Dual crop coefficient (K_{cb})	Does not require adjustment	~ crop height ~ min. RH ~ wind	~ crop height ~ min. RH ~ wind ~ desired harvest conditions

Modifying the Mid- and End-Season Crop Coefficient Values

Locales having weather parameters that differ from those used in FAO-56 can have their mid- and end-coefficient values adjusted using an equation from FAO-56 (Allen, et al., 1998):

$$K_{c\_Adj} = K_{c\_FAO-56} + \left[0.04(u_2 - 2) - 0.004(RH_{\min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \qquad \text{Eq. 3}$$

Where:

K_{c_Adj} is the adjusted mid- or end-season coefficient value
K_{c_FAO-56} is the FAO-56 mid- or end-season coefficient value

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[2] These ranges for the crop coefficient values are time-period averaged since actual day-to-day swings in values occur for various reasons and will greatly exceed 1.20 (see Figure 2).

u_2 is mean value for daily wind speed at 2 m height during mid- or end-season period[3]
RH_{min} is mean value for daily minimum RH during mid- or end-season period
h is mean plant height during mid- or end-season period

Note that Eq. 3 produces a “tack-on” value that will be either added to (if positive) or subtracted from (if negative) to the default FAO-56 mid- or end-season crop coefficient value. This tack-on value is the *climate adjustment offset* (adj_{clim}). Both wind speed and minimum relative humidity data are based on long-term averages.

Although Eq. 3 is straight forward, it may be difficult to obtain the needed long-term weather data to calculate the adj_{clim} offset value. To rectify this, the adj_{clim} offset values by month have been calculated for 177 cities in the USA and its possessions, plus Algiers City, Algeria (Table 2). The table includes the offset portion of Eq. 3 calculated using long-term climatic databases on monthly mean wind speed and afternoon relative humidity maintained by NOAA (USDC, 2009). Table 2 values are based on an average plant height of two feet. If the height of the crop in question differs from 2 feet then it needs to be adjusted. Table 2 includes an inset table with height adjustment factors (adj_h) that can be used to make the correct conversion (by: adj_{clim} x adj_h). An example of using this procedure to modify default FAO-56 mid- and end-crop coefficient values follows.

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[3] If the local wind speed data is taken from an anemometer set at a height other then 2 m it should be modified (a simple equation is found in FAO-56).

Adjusting K_{c_mid} and K_{c_end} to Reflect Local Deviation from RH_{min} of 45% and Wind of 4 1/2 mph

Given:

Crop = sweet corn
Location = Fresno, CA
Planting date = Jan 15

Find:

Modified values for: K_{c_mid} and K_{c_end}

Procedure:

- Get default K_c values from FAO-56 ($K_{c\_FAO\text{-}56}$).
- Based on location/month find the climate adjustment factor (adj_{clim}) to be +/- to $K_{c\_FAO\text{-}56}$.
- Using inset table in Table 3to find height adjustment factor (adj_h) and multiply adj_{clim} by adj_h.
- Add this product to the original default value from FAO-56 ($K_{c\_FAO\text{-}56}$).

Results:

K_{c_mid} = 1.15 (FAO-56)
K_{c_end} = 1.05 (FAO-56)
K_{c_mid} : appears to occur April (FAO-56)
K_{c_end} : appears to occur May (FAO-56)
estimated height during mid period ≈ 5 ft
estimated height during end period ≈ 6 ft

Modified $K_{c\_mid} = K_{c\_FAO\text{-}56} + (adj_{clim})\ (adj_h) = 1.15 + (0.06)\ (1.32) = 1.23$

Modified $K_{c\_end} = K_{c\_FAO\text{-}56} + (adj_{clim})\ (adj_h) = 1.05 + (0.09)\ (1.39) = 1.18$

Table 2. Adjustment Factor to be Added to Default Mid and End Crop Coefficients of FAO-56 to Account for Wind Speed other then 2.0 m/s and RH_{min} other then 45% -- Based on Plant Height of 2.0 feet. (Adjust heights other than 2.0 feet by inset table [light blue] below).

Plant Height (ft)	**0.5**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Height Adjustment Factor (adj_h):	0.66	0.81	1.00	1.13	1.23	1.32	1.39	1.46	1.52

LOCATION	Wind Data * YRS	RH Data * YRS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HUNTSVILLE, AL	39	39	-0.01	0.01	0.02	0.02	0.00	-0.02	-0.04	-0.04	-0.02	-0.01	-0.01	-0.01
MOBILE, AL	58	44	0.01	0.02	0.03	0.03	0.00	-0.01	-0.03	-0.03	-0.02	0.00	0.00	0.00
FAIRBANKS, AK	55	54	-0.08	-0.06	-0.01	0.03	0.05	0.04	0.01	-0.01	-0.01	-0.05	-0.08	-0.09
HOMER, AK	32	57	-0.04	-0.03	-0.01	0.00	0.00	-0.01	-0.03	-0.04	-0.03	-0.02	-0.03	-0.04
JUNEAU, AK	61	40	-0.04	-0.02	-0.01	0.01	0.01	0.00	-0.02	-0.03	-0.03	-0.02	-0.04	-0.04
PHOENIX, AZ	61	46	0.04	0.06	0.08	0.10	0.11	0.11	0.09	0.08	0.08	0.07	0.06	0.04
TUCSON, AZ	61	66	0.07	0.08	0.10	0.12	0.13	0.13	0.09	0.07	0.09	0.09	0.08	0.07
WINSLOW, AZ	46	29	0.03	0.08	0.11	0.14	0.14	0.14	0.10	0.08	0.08	0.08	0.06	0.02
YUMA, AZ	28	14	0.07	0.08	0.10	0.11	0.12	0.12	0.11	0.10	0.08	0.08	0.07	0.06
FORT SMITH, AR	61	42	-0.01	0.00	0.02	0.02	-0.01	-0.02	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01
LITTLE ROCK, AR	64	42	-0.01	0.00	0.02	0.01	-0.01	-0.01	-0.02	-0.02	-0.02	-0.01	0.00	-0.01
BAKERSFIELD, CA	54	30	-0.04	0.00	0.02	0.06	0.08	0.09	0.09	0.08	0.06	0.04	-0.01	-0.03
FRESNO, CA	57	43	-0.05	-0.01	0.02	0.06	0.09	0.10	0.09	0.08	0.06	0.04	-0.02	-0.05
LONG BEACH, CA	37	36	-0.01	-0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01
LOS ANGELES C.O., CA	32	47	0.00	0.00	0.00	-0.01	-0.01	-0.02	-0.02	-0.02	-0.01	-0.02	0.01	0.01
SAN DIEGO, CA	66	46	-0.02	-0.01	0.00	0.00	-0.01	-0.02	-0.02	-0.02	-0.02	-0.03	-0.02	-0.02
SAN FRANCISCO C.O., CA	28	8	-0.02	-0.01	0.00	0.02	0.01	0.03	0.02	0.02	0.02	0.01	0.00	0.00
SANTA BARBARA, CA	35	7	-0.02	-0.02	-0.01	0.00	-0.02	-0.02	-0.02	-0.03	-0.03	-0.03	-0.02	-0.03
SANTA MARIA, CA	26	30	-0.02	-0.01	-0.01	0.00	0.00	0.00	-0.02	-0.02	-0.03	-0.03	-0.02	-0.02
STOCKTON, CA	46	30	-0.04	-0.01	0.02	0.05	0.08	0.09	0.09	0.08	0.06	0.04	-0.01	-0.04
ALAMOSA, CO	15	49	-0.01	0.02	0.07	0.10	0.10	0.10	0.05	0.04	0.06	0.05	0.01	-0.02
DENVER, CO	50	38	0.04	0.05	0.07	0.09	0.07	0.08	0.07	0.07	0.07	0.06	0.03	0.03

GRAND JUNCTION, CO	60	43	-0.03	0.02	0.07	0.10	0.11	0.12	0.11	0.10	0.10	0.07	0.02	-0.02
PUEBLO, CO	51	27	0.03	0.06	0.09	0.10	0.09	0.10	0.08	0.06	0.07	0.06	0.03	0.02
HARTFORD, CT	52	47	0.02	0.03	0.05	0.06	0.04	0.02	0.02	0.01	0.01	0.02	0.02	0.01
WILMINGTON, DE	58	59	0.02	0.04	0.05	0.05	0.03	0.02	0.01	0.01	0.01	0.02	0.03	0.02
DAYTONA BEACH, FL	61	62	0.02	0.03	0.03	0.03	0.02	-0.01	-0.02	-0.02	-0.01	0.01	0.01	0.01
FORT MYERS, FL	61	62	0.02	0.03	0.04	0.04	0.03	0.00	-0.01	-0.01	-0.01	0.02	0.01	0.01
GAINESVILLE, FL	23	23	-0.01	0.00	0.02	0.02	0.01	-0.01	-0.02	-0.03	-0.03	-0.02	-0.01	-0.02
JACKSONVILLE, FL	57	70	0.01	0.03	0.04	0.04	0.03	0.01	0.00	-0.01	-0.01	0.00	0.01	0.00
KEY WEST, FL	53	58	0.02	0.03	0.03	0.04	0.02	0.00	0.00	0.00	0.00	0.01	0.02	0.02
MIAMI, FL	57	42	0.02	0.03	0.04	0.04	0.02	-0.01	-0.01	-0.01	-0.01	0.01	0.02	0.01
TALLAHASSEE, FL	45	45	-0.01	0.01	0.02	0.02	0.01	-0.01	-0.03	-0.03	-0.02	0.00	-0.01	-0.01
TAMPA, FL	60	43	0.01	0.02	0.03	0.04	0.03	0.00	-0.02	-0.02	-0.01	0.01	0.01	0.01
ATHENS, GA	51	51	0.01	0.02	0.03	0.03	0.01	0.00	-0.01	-0.02	-0.01	0.00	0.01	0.01
ATLANTA, GA	68	46	0.03	0.04	0.06	0.05	0.03	0.01	0.00	0.00	0.01	0.02	0.03	0.03
AUGUSTA,GA	55	42	0.01	0.02	0.03	0.03	0.01	0.00	-0.01	-0.02	-0.01	0.00	0.00	0.01
MACON, GA	58	42	0.01	0.02	0.03	0.03	0.02	0.01	0.00	-0.01	0.00	0.01	0.01	0.01
HILO, HI	57	57	-0.02	-0.01	-0.02	-0.02	-0.02	-0.02	-0.03	-0.03	-0.03	-0.03	-0.04	-0.03
HONOLULU,HI	57	37	0.01	0.03	0.04	0.05	0.06	0.07	0.08	0.07	0.05	0.04	0.03	0.03
KAHULUI, HI	34	42	0.03	0.04	0.05	0.07	0.07	0.09	0.10	0.09	0.07	0.05	0.04	0.03
LIHUE, HI	56	57	0.02	0.03	0.04	0.05	0.04	0.05	0.05	0.04	0.03	0.03	0.03	0.03
BOISE, ID	67	67	-0.02	0.01	0.07	0.08	0.08	0.09	0.10	0.10	0.08	0.06	0.01	-0.02
POCATELLO, ID	54	43	0.00	0.02	0.06	0.10	0.09	0.10	0.10	0.11	0.09	0.08	0.02	-0.01
CHICAGO,IL	48	48	0.02	0.02	0.03	0.05	0.03	0.02	0.00	0.00	0.01	0.02	0.02	0.01
MOLINE, IL	63	46	0.01	0.01	0.03	0.05	0.03	0.01	-0.01	-0.02	-0.01	0.02	0.02	0.00
SPRINGFIELD, IL	59	47	0.02	0.02	0.04	0.05	0.04	0.02	0.00	-0.01	0.00	0.02	0.03	0.01
EVANSVILLE, IN	66	45	-0.01	0.00	0.02	0.02	0.00	-0.01	-0.03	-0.03	-0.02	-0.01	-0.01	-0.01
INDIANAPOLIS, IN	58	47	0.01	0.02	0.04	0.05	0.03	0.01	0.00	-0.01	0.01	0.02	0.02	0.00
DES MOINES, IA	57	45	0.01	0.02	0.04	0.06	0.04	0.02	0.00	0.00	0.01	0.02	0.02	0.01
SIOUX CITY, IA	65	47	0.01	0.01	0.03	0.06	0.04	0.02	0.00	0.00	0.01	0.03	0.02	0.00
WATERLOO, IA	50	47	0.01	0.01	0.03	0.05	0.04	0.02	-0.01	-0.01	0.00	0.02	0.01	0.00
CONCORDIA, KS	44	44	0.02	0.03	0.06	0.07	0.04	0.04	0.04	0.03	0.04	0.05	0.03	0.02
DODGE CITY, KS	64	43	0.06	0.07	0.09	0.10	0.08	0.08	0.08	0.07	0.08	0.08	0.07	0.06
GOODLAND, KS	58	40	0.05	0.07	0.10	0.12	0.10	0.10	0.10	0.09	0.09	0.08	0.05	0.05
TOPEKA, KS	57	42	0.00	0.01	0.04	0.04	0.02	0.00	0.00	-0.01	0.00	0.01	0.01	0.00
WICHITA, KS	53	53	0.03	0.04	0.07	0.08	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.03
JACKSON, KY	25	25	-0.02	-0.01	0.01	0.02	-0.02	-0.04	-0.04	-0.05	-0.03	-0.01	-0.01	-0.02

LOUISVILLE, KY	59	46	0.01	0.02	0.04	0.04	0.01	0.00	0.00	-0.01	0.00	0.01	0.01	0.00
PADUCAH KY	22	22	-0.02	-0.02	0.00	0.00	-0.03	-0.05	-0.05	-0.06	-0.05	-0.04	-0.02	-0.03
BATON ROUGE, LA	55	47	-0.01	0.00	0.01	0.00	-0.01	-0.03	-0.04	-0.04	-0.03	-0.02	-0.01	-0.01
LAKE CHARLES, LA	45	42	-0.01	0.00	0.00	0.00	-0.01	-0.03	-0.05	-0.04	-0.03	-0.01	-0.01	-0.01
NEW ORLEANS, LA	58	58	-0.01	0.01	0.01	0.01	-0.01	-0.03	-0.04	-0.04	-0.03	-0.01	0.00	-0.01
SHREVEPORT, LA	54	54	0.00	0.01	0.02	0.01	0.00	-0.01	-0.01	-0.02	-0.01	0.00	0.00	0.00
PORTLAND, ME	66	66	0.01	0.02	0.03	0.04	0.02	0.00	0.00	0.00	0.00	0.01	0.01	0.01
BALTIMORE, MD	56	53	0.02	0.04	0.06	0.06	0.03	0.03	0.01	0.01	0.01	0.02	0.02	0.02
BLUE HILL, MA	65	53	0.10	0.11	0.11	0.11	0.09	0.07	0.07	0.06	0.07	0.09	0.09	0.10
WORCESTER, MA	40	51	0.05	0.05	0.06	0.06	0.05	0.02	0.01	0.01	0.01	0.03	0.03	0.03
GRAND RAPIDS, MI	43	43	0.01	0.01	0.03	0.05	0.04	0.02	0.02	0.01	0.01	0.01	0.01	0.00
LANSING, MI	47	43	0.01	0.02	0.03	0.05	0.04	0.02	0.01	0.00	0.00	0.01	0.01	0.00
DULUTH, MN	57	45	0.01	0.02	0.03	0.05	0.05	0.02	0.01	0.00	0.01	0.02	0.01	0.00
ROCHESTER, MN	46	46	0.03	0.03	0.04	0.06	0.05	0.04	0.02	0.01	0.02	0.04	0.03	0.02
SAINT CLOUD, MN	20	54	-0.02	-0.01	0.00	0.03	0.03	0.00	-0.01	-0.02	-0.01	0.00	-0.02	-0.03
JACKSON, MS	43	43	-0.02	0.00	0.00	0.00	-0.02	-0.03	-0.04	-0.04	-0.03	-0.02	-0.02	-0.02
MERIDIAN, MS	47	42	-0.02	-0.01	0.00	-0.01	-0.03	-0.04	-0.05	-0.05	-0.04	-0.03	-0.02	-0.03
TUPELO, MS	23	23	-0.03	-0.02	-0.01	-0.01	-0.03	-0.05	-0.05	-0.05	-0.04	-0.04	-0.03	-0.03
COLUMBIA, MO	36	37	0.01	0.01	0.03	0.04	0.00	-0.01	-0.01	-0.01	0.00	0.01	0.01	0.00
ST. LOUIS, MO	57	46	0.01	0.02	0.04	0.04	0.01	0.01	0.00	-0.01	0.00	0.01	0.01	0.00
SPRINGFIELD, MO	61	46	0.02	0.03	0.05	0.05	0.01	0.00	0.00	0.00	0.00	0.03	0.03	0.02
BILLINGS, MT	67	47	0.06	0.07	0.07	0.09	0.08	0.08	0.09	0.10	0.09	0.08	0.07	0.07
GREAT FALLS, MT	65	45	0.07	0.08	0.08	0.10	0.09	0.08	0.10	0.10	0.09	0.10	0.08	0.08
HELENA, MT	66	41	-0.02	0.01	0.04	0.07	0.07	0.06	0.08	0.07	0.06	0.03	0.00	-0.02
MISSOULA, MT	62	46	-0.07	-0.04	0.01	0.04	0.04	0.04	0.06	0.06	0.03	0.00	-0.06	-0.08
GRAND ISLAND, NE	57	45	0.03	0.03	0.05	0.08	0.06	0.05	0.03	0.02	0.04	0.05	0.04	0.03
LINCOLN, NE	34	34	0.00	0.00	0.03	0.05	0.02	0.02	0.01	0.00	0.01	0.02	0.01	0.00
NORFOLK, NE	30	61	0.03	0.02	0.04	0.07	0.05	0.04	0.02	0.02	0.03	0.05	0.03	0.02
NORTH PLATTE, NE	54	42	0.00	0.01	0.04	0.06	0.04	0.03	0.02	0.02	0.03	0.03	0.01	0.00
OMAHA (NORTH), NE	9	9	0.02	0.01	0.03	0.04	0.02	0.02	-0.01	-0.01	0.01	0.03	0.01	0.00
SCOTTSBLUFF, NE	55	41	0.04	0.06	0.09	0.10	0.09	0.08	0.08	0.07	0.07	0.07	0.04	0.03
VALENTINE, NE	38	39	0.00	0.00	0.02	0.05	0.04	0.03	0.02	0.03	0.04	0.03	0.02	0.01
ELY, NV	65	54	0.04	0.05	0.08	0.10	0.11	0.12	0.13	0.12	0.12	0.10	0.06	0.04
LAS VEGAS, NV	58	46	0.06	0.09	0.12	0.14	0.15	0.15	0.14	0.13	0.12	0.10	0.08	0.07
RENO, NV	64	43	0.00	0.03	0.07	0.08	0.09	0.09	0.10	0.09	0.07	0.06	0.02	0.00
WINNEMUCCA, NV	50	57	0.00	0.03	0.07	0.08	0.09	0.10	0.12	0.11	0.10	0.07	0.03	0.00

CONCORD, NH	64	41	0.00	0.02	0.02	0.04	0.02	0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01
NEWARK, NJ	62	41	0.04	0.06	0.07	0.07	0.05	0.04	0.03	0.03	0.03	0.03	0.04	0.04
ALBUQUERQUE, NM	67	46	0.06	0.08	0.11	0.13	0.13	0.13	0.09	0.08	0.08	0.08	0.06	0.04
CLAYTON, NM	14	49	0.08	0.09	0.12	0.14	0.12	0.12	0.09	0.07	0.09	0.09	0.08	0.07
ROSWELL, NM	33	33	0.05	0.08	0.11	0.12	0.11	0.11	0.08	0.06	0.06	0.06	0.05	0.04
ALBANY, NY	68	41	0.01	0.03	0.05	0.06	0.03	0.02	0.01	0.00	0.00	0.01	0.01	0.00
BINGHAMTON, NY	55	55	0.01	0.02	0.03	0.05	0.04	0.02	0.01	0.01	0.00	0.02	0.01	0.01
BUFFALO, NY	67	46	0.04	0.04	0.05	0.06	0.05	0.04	0.04	0.03	0.03	0.04	0.03	0.03
SYRACUSE, NY	57	43	0.01	0.02	0.03	0.05	0.03	0.02	0.01	0.00	0.00	0.01	0.01	0.00
ASHEVILLE, NC	42	42	0.02	0.03	0.03	0.03	0.00	-0.02	-0.03	-0.04	-0.03	0.00	0.01	0.01
CHARLOTTE, NC	57	46	0.01	0.03	0.04	0.04	0.02	0.00	0.00	-0.01	0.00	0.01	0.01	0.01
RALEIGH, NC	57	42	0.02	0.03	0.04	0.05	0.02	0.00	-0.01	-0.01	-0.01	0.00	0.01	0.01
WILMINGTON, NC	55	43	0.03	0.04	0.05	0.05	0.03	0.01	0.00	-0.01	-0.01	0.01	0.02	0.02
BISMARCK, ND	67	47	0.00	0.00	0.02	0.05	0.05	0.03	0.03	0.03	0.03	0.03	0.00	-0.01
FARGO, ND	64	47	0.02	0.02	0.03	0.06	0.07	0.04	0.03	0.04	0.04	0.04	0.03	0.01
WILLISTON, ND	42	45	-0.02	-0.01	0.01	0.05	0.05	0.03	0.03	0.03	0.03	0.03	-0.01	-0.02
AKRON, OH	58	43	0.02	0.02	0.04	0.05	0.03	0.01	0.01	0.00	0.00	0.02	0.02	0.01
COLUMBUS, OH	57	47	0.00	0.01	0.04	0.04	0.02	0.01	0.00	-0.01	-0.01	0.01	0.01	0.00
DAYTON, OH	63	43	0.01	0.02	0.04	0.05	0.03	0.02	0.01	0.00	0.01	0.02	0.02	0.01
MANSFIELD, OH	22	40	0.02	0.02	0.03	0.05	0.03	0.01	0.00	0.00	0.00	0.02	0.02	0.01
OKLAHOMA CITY, OK	58	41	0.04	0.05	0.08	0.08	0.04	0.04	0.04	0.04	0.03	0.05	0.05	0.04
TULSA, OK	58	46	0.02	0.03	0.05	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.02
ASTORIA, OR	53	53	-0.03	-0.02	-0.02	-0.01	-0.01	-0.02	-0.01	-0.02	-0.03	-0.04	-0.04	-0.04
EUGENE, OR	54	49	-0.05	-0.03	-0.01	0.00	0.01	0.02	0.06	0.05	0.04	-0.02	-0.05	-0.06
MEDFORD, OR	57	45	-0.07	-0.03	0.00	0.01	0.03	0.05	0.06	0.06	0.04	0.00	-0.06	-0.08
PENDLETON, OR	53	65	-0.04	-0.01	0.04	0.07	0.07	0.09	0.10	0.10	0.08	0.03	-0.02	-0.04
SALEM, OR	58	44	-0.04	-0.02	0.00	0.00	0.00	0.01	0.04	0.04	0.02	-0.02	-0.05	-0.05
GUAM, PC	16	13	0.00	0.02	0.02	0.01	-0.01	-0.02	-0.05	-0.05	-0.06	-0.05	-0.02	0.00
JOHNSTON ISLAND, PC	23	23	0.05	0.07	0.08	0.07	0.06	0.07	0.07	0.06	0.04	0.05	0.06	0.07
KOROR, PC	41	55	-0.04	-0.04	-0.04	-0.04	-0.06	-0.06	-0.06	-0.05	-0.05	-0.05	-0.06	-0.05
KWAJALEIN, MARSHALL IS., PC	40	46	0.07	0.07	0.07	0.05	0.03	0.02	-0.01	-0.02	-0.03	-0.02	0.01	0.06
MAJURO, MARSHALL IS, PC	42	51	0.02	0.02	0.02	0.01	-0.01	-0.02	-0.04	-0.04	-0.05	-0.04	-0.03	0.00
PAGO PAGO, AMER SAMOA, PC	39	38	-0.02	-0.02	-0.03	-0.03	-0.01	0.01	0.02	0.02	0.02	0.01	-0.01	-0.02
POHNPEI, CAROLINE IS., PC	32	36	-0.04	-0.03	-0.04	-0.06	-0.06	-0.07	-0.08	-0.08	-0.08	-0.08	-0.08	-0.06
CHUUK, E. CAROLINE IS., PC	41	36	0.00	0.00	0.00	-0.02	-0.03	-0.05	-0.05	-0.04	-0.04	-0.04	-0.04	-0.02
WAKE ISLAND, PC	43	45	0.05	0.05	0.06	0.07	0.05	0.03	0.03	0.02	0.02	0.04	0.07	0.06

YAP, W CAROLINE IS., PC	37	58	-0.02	-0.01	-0.01	-0.02	-0.04	-0.05	-0.05	-0.05	-0.05	-0.06	-0.05	-0.03
ALLENTOWN, PA	57	56	0.02	0.03	0.05	0.05	0.03	0.02	0.01	0.00	0.00	0.01	0.02	0.02
ERIE, PA.	52	41	0.03	0.02	0.03	0.03	0.02	0.01	0.01	0.00	0.01	0.03	0.04	0.03
PITTSBURGH, PA	54	46	0.01	0.02	0.04	0.05	0.03	0.02	0.01	0.00	0.00	0.02	0.02	0.01
AVOCA, PA	51	51	0.00	0.01	0.03	0.04	0.03	0.01	0.01	0.00	0.00	0.00	0.00	-0.01
PROVIDENCE, RI	53	43	0.04	0.06	0.06	0.07	0.05	0.03	0.03	0.03	0.03	0.03	0.04	0.04
CHARLESTON AP,SC	57	64	0.03	0.04	0.05	0.05	0.03	0.01	0.00	-0.01	-0.01	0.01	0.02	0.02
COLUMBIA, SC	58	40	0.01	0.03	0.04	0.05	0.02	0.01	0.00	-0.01	-0.01	0.00	0.01	0.01
GREENVILLE-SPARTANBURG AP, SC	44	44	0.01	0.02	0.03	0.03	0.01	0.00	-0.01	-0.02	-0.01	0.01	0.01	0.01
ABERDEEN, SD	30	38	0.00	0.00	0.02	0.05	0.05	0.02	0.01	0.02	0.03	0.03	0.00	-0.01
HURON, SD	67	47	0.01	0.01	0.03	0.06	0.05	0.03	0.03	0.03	0.04	0.04	0.03	0.01
RAPID CITY, SD	56	56	0.02	0.04	0.07	0.09	0.08	0.06	0.07	0.09	0.09	0.07	0.04	0.02
SIOUX FALLS, SD	58	43	0.01	0.01	0.03	0.06	0.04	0.03	0.02	0.01	0.02	0.03	0.01	0.00
CHATTANOOGA, TN	66	76	-0.01	0.00	0.02	0.02	0.00	-0.02	-0.02	-0.03	-0.02	-0.02	-0.01	-0.02
KNOXVILLE, TN	64	46	-0.01	0.00	0.02	0.03	0.00	-0.01	-0.02	-0.03	-0.02	-0.01	-0.01	-0.01
MEMPHIS, TN	58	67	0.01	0.02	0.04	0.04	0.01	0.00	-0.01	-0.01	0.00	0.01	0.02	0.01
NASHVILLE, TN	65	41	0.00	0.01	0.03	0.02	-0.01	-0.01	-0.02	-0.03	-0.02	-0.01	0.00	0.00
ABILENE, TX	62	43	0.05	0.06	0.08	0.09	0.06	0.06	0.05	0.05	0.03	0.05	0.05	0.05
AMARILLO, TX	65	45	0.07	0.08	0.11	0.12	0.10	0.09	0.08	0.07	0.07	0.08	0.08	0.07
AUSTIN, TX	65	45	0.00	0.01	0.02	0.02	0.01	0.00	0.01	0.01	-0.01	0.00	0.00	0.00
CORPUS CHRISTI, TX	64	42	0.02	0.03	0.05	0.05	0.03	0.02	0.02	0.02	0.01	0.02	0.03	0.02
DALLAS-FORT WORTH, TX	53	43	0.03	0.04	0.05	0.05	0.02	0.03	0.03	0.02	0.02	0.02	0.03	0.03
EL PASO, TX	64	46	0.07	0.10	0.13	0.14	0.14	0.12	0.08	0.07	0.07	0.07	0.07	0.06
GALVESTON, TX	60	96	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.00
HOUSTON, TX	37	37	-0.02	-0.01	0.00	0.00	-0.02	-0.02	-0.03	-0.03	-0.03	-0.02	-0.02	-0.02
LUBBOCK, TX	57	59	0.06	0.08	0.11	0.12	0.10	0.09	0.06	0.04	0.04	0.06	0.07	0.06
MIDLAND-ODESSA, TX	53	43	0.05	0.06	0.09	0.10	0.09	0.08	0.07	0.05	0.04	0.05	0.05	0.05
PORT ARTHUR, TX	53	46	0.00	0.02	0.02	0.02	0.00	-0.02	-0.03	-0.03	-0.02	0.00	0.00	0.00
SAN ANGELO, TX	57	46	0.03	0.05	0.07	0.07	0.05	0.04	0.04	0.03	0.01	0.02	0.03	0.03
SAN ANTONIO, TX	64	64	0.01	0.02	0.03	0.03	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01
VICTORIA, TX	45	45	0.00	0.02	0.03	0.03	0.01	0.00	0.00	0.00	-0.01	0.00	0.00	0.00
WACO, TX	57	43	0.02	0.03	0.04	0.04	0.02	0.03	0.04	0.04	0.02	0.02	0.02	0.02
WICHITA FALLS, TX	58	46	0.04	0.05	0.07	0.07	0.05	0.05	0.06	0.05	0.03	0.04	0.04	0.04
BURLINGTON, VT	63	41	0.01	0.02	0.02	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01
LYNCHBURG, VA	39	43	0.02	0.02	0.03	0.04	0.01	-0.01	-0.02	-0.02	-0.01	0.00	0.01	0.01
NORFOLK, VA	58	58	0.04	0.05	0.06	0.07	0.04	0.03	0.01	0.01	0.02	0.03	0.04	0.04

ROANOKE, VA	58	42	0.04	0.04	0.06	0.05	0.02	0.00	0.00	-0.01	-0.01	0.01	0.02	0.03
OLYMPIA, WA	53	46	-0.06	-0.04	-0.01	0.00	0.00	0.00	0.01	0.01	-0.01	-0.04	-0.06	-0.07
QUILLAYUTE, WA	40	40	-0.07	-0.05	-0.05	-0.04	-0.04	-0.04	-0.04	-0.05	-0.05	-0.07	-0.08	-0.08
SPOKANE, WA	59	47	-0.04	-0.01	0.04	0.06	0.06	0.08	0.09	0.09	0.07	0.03	-0.03	-0.05
YAKIMA, WA	52	57	-0.06	-0.01	0.05	0.08	0.08	0.08	0.09	0.08	0.07	0.03	-0.03	-0.07
SAN JUAN, PR	51	51	0.00	0.00	0.01	0.01	-0.01	0.00	0.00	-0.01	-0.02	-0.03	-0.02	-0.01
CHARLESTON, WV	59	59	-0.02	-0.01	0.01	0.02	0.00	-0.02	-0.03	-0.03	-0.03	-0.02	-0.01	-0.02
HUNTINGTON, WV	44	45	-0.02	0.00	0.02	0.03	0.00	-0.02	-0.03	-0.03	-0.03	-0.01	-0.01	-0.02
GREEN BAY, WI	57	45	0.00	0.00	0.01	0.03	0.02	0.01	0.00	-0.02	-0.01	0.01	0.00	-0.01
LA CROSSE, WI	54	45	-0.01	-0.01	0.01	0.04	0.03	0.01	0.00	-0.01	0.00	0.01	0.00	-0.02
MADISON, WI	60	47	0.00	0.01	0.02	0.04	0.03	0.01	-0.01	-0.01	-0.01	0.01	0.00	-0.01
CASPER, WY	56	42	0.09	0.09	0.10	0.10	0.09	0.10	0.11	0.11	0.11	0.09	0.08	0.08
LANDER, WY	60	60	-0.02	0.00	0.03	0.05	0.06	0.07	0.08	0.08	0.06	0.03	-0.01	-0.02
SHERIDAN, WY	63	42	-0.01	0.00	0.04	0.06	0.05	0.04	0.06	0.07	0.05	0.03	-0.01	-0.01
ALGIERS CITY, ALGERIA	1	1	-0.05	-0.03	-0.02	-0.01	-0.07	-0.04	-0.02	-0.08	-0.05	-0.06	-0.07	-0.07

* Data ending 2006.

Modifying the Initial Crop Coefficient Value

It is the initial crop coefficient (K_{c_ini}) that will be the coefficient that will likely deviate the most from FAO-56 default values, due mostly to variations in wetting frequencies between various regions. For this reason FAO-56 clearly states that regions "are subject to the effects of large variations in wetting frequencies and therefore **refinements to the value used for K_{c_ini} should always be made"** (Allen et al., 1998) (emphasis by the authors). The K_{c_ini} values for various field crops in FAO-56 ranges around 0.3 to 0.4. However, when there are a significant number of rain/irrigation events this value could be off by as much as 200%. Examining data from Missouri shows that K_{c_ini} values needed to be doubled in many cases.

The adjusted K_{c_ini} value is graphically solved for using figures from FAO-56 that require (1) ET_o (in mm) and (2) wetting interval (in days) data during the initial period. Unfortunately, the required long-term climatic data needed for the graphical are hard to obtain, especially local wetting interval information. To obtain this data one would to need to look at several years of rainfall patterns. In addition, wetting events on two or more consecutive days is considered just one single wetting event, so weather files need to be gone over by hand. Fortunately, the U.S. Department of Commerce maintains on-line climatic databases for about 300 cities in the USA and its possessions (U.S. Department of Commerce, 2008). Because both ET_o and wetting frequency data are both required in the graphical solution, the list pares down to 180 useable locations. Table 3 lists frequency of rainfall events by month (contiguous rainfall days accounted for) for these cities in the USA and her possessions, plus Algiers City, Algeria. Table 3 also includes average daily ET_o data.

In order to make use of the USDC/NOAA data on average number of rainfall events > 0.01 inches per month an estimate is needed of the ratio of total non-contiguous rainfall events to the number of total rainfall events, which the NOAA dataset reports. This was done by counting total and total non-contiguous events for a subset of eight cities spread throughout the USA for the months Mar-June for the years 2000, 2002, 2004 and 2008. To account for the different number of days that can occur in a month (28, 29, 30 or 31) percentages were used. Different response equations were developed for sub-humid sites and arid sites (the demarcation between the two being 10 inches (250 mm) of total rain for the March to May period. Figure 3 shows the relationship of frequency of occurrence of total non-contiguous rainfall events to number of total individual rainfall events; the linear equation for both broad climate types can be seen within the figure. The number of total non-contiguous rainfall events each month was calculated based on climate type and then converted into the wetting interval for all the involved cities. Table 3 has both the frequency and average daily ET_o data.

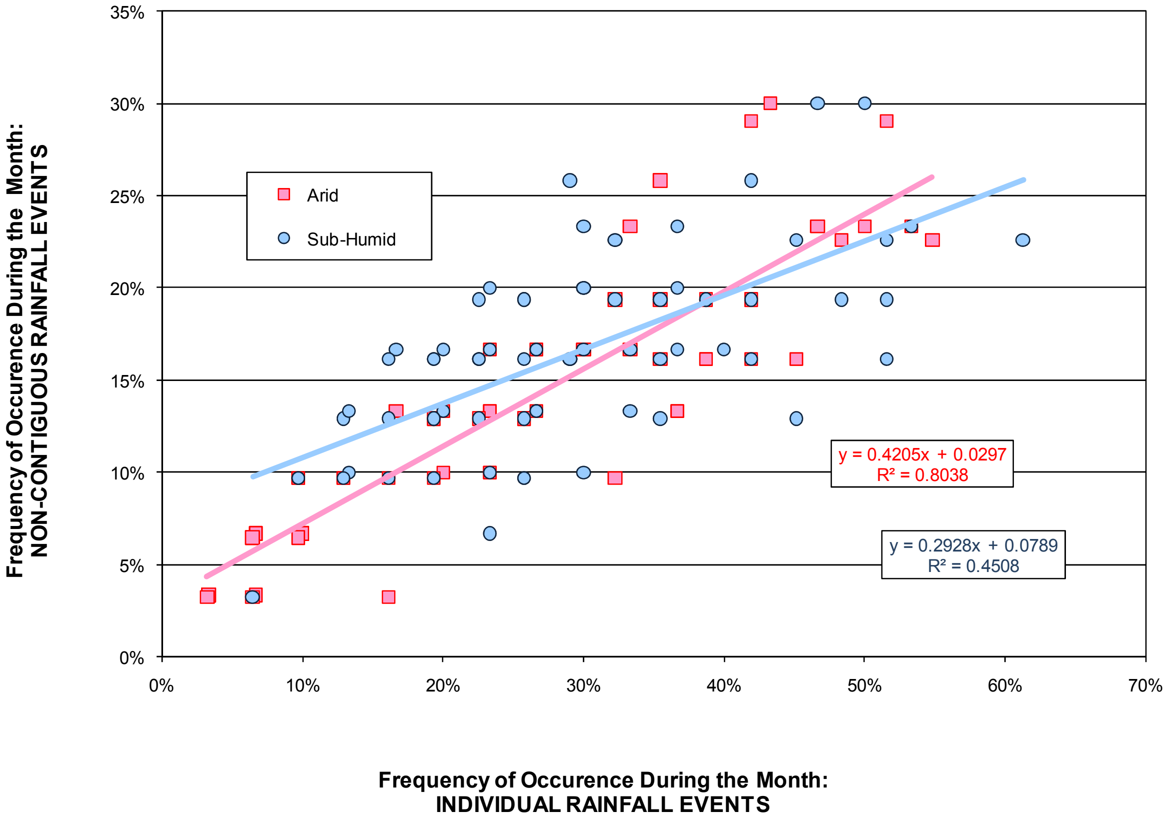


Figure 3 Relationship between frequency of occurrence of total non-contiguous rainfall events to total number of individual rainfall events in a month for arid and sub-humid regions.

The interval between wetting events in Table 3 does not account for wetting events that occur due to irrigation. If irrigation occurs then the interval between wetting events will decrease. Equation 4 shows how to calculate the new frequency interval of Table 3 should irrigation(s) take place.

The new frequency can be estimated by equation 4.

$$Freq_{New} = \frac{30}{\left(\frac{30}{Freq_{Table}}\right) + Irrs} \qquad \text{(Eq. 4)}$$

Where

$Freq_{New}$ = The new interval between wetting events due to irrigation, days
$Freq_{Table}$ = Interval from Table 3, days
Irrs = The number of irrigations that will occur during the initial period

An example of how the default K_{c_ini} value can be adjusted using this procedure is seen below.

Adjusting K_{c_ini} Based on ET_o and Rainfall/Irrigation Events and FAO-56.

Given:

Crop = soybean
Location = Omaha, NE
Planting date = Apr 10

Find:

Modified K_{c_ini} with no irrigation & for 1 irrigation for that period.

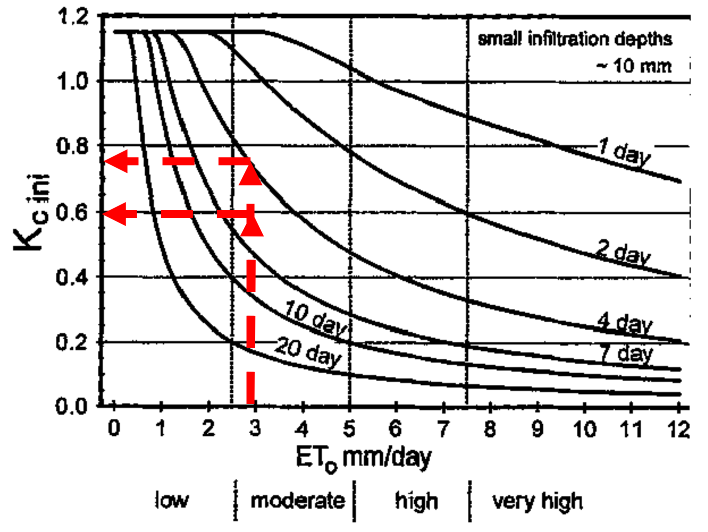
Procedure:

- Get frequency of rainfall events for Omaha, NE in April from Table 3.
- Get ET_o for Omaha, NE in April from Table 3.
- Plot those values on Figs. 29, 30, or 31 (dependent on soil/wetting amount) in FAO-56 to get K_{c_ini}.
- Recalculate interval to include the expected irrigation(s); re-plot using the new interval to get K_{c_ini} when irrigation occurs.

Results:

K_{c_ini} = 0.40 (Table 12, FAO-56)
ET_o in Apr = 2.8 mm (Table 3)
Wetting Frequency in Apr = 5 days (Table 3)
New Wetting Frequency in Apr = 4 days (Eq. 4)

$$Freq_{New} = \frac{30}{(\frac{30}{Freq_{Table}}) + Irrs} = \frac{30}{(\frac{30}{5}) + 1} = 4\ days$$



Answer:

K_{c_ini} = 0.60 (no irrigation) – increased 50% from default value.
K_{c_ini} = 0.75 (1 irrigation) – increased 88% from default value.

Table 3. Interval between non-contiguous rainfall events (days) and average daily ET_o as calculated by Hargreaves-Samani (mm) by month.

Location	YRS of Data	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	rain / ETo	-- Interval between Rainfall Events (days) / average daily ET_o (mm) --											
HUNTSVILLE, AL	39 / 30	5 / 1.2	6 / 1.8	5 / 3.2	6 / 4.4	6 / 5.2	6 / 5.8	6 / 5.7	6 / 5.2	6 / 4.1	7 / 3.1	6 / 2.	6 / 1.5
MOBILE, AL	65 / 30	6 / 1.8	6 / 2.4	6 / 3.4	7 / 4.5	6 / 5.2	5 / 5.7	5 / 5.5	5 / 5.	6 / 4.3	8 / 3.4	7 / 2.4	6 / 1.8
FAIRBANKS, AK	55 / 30	8 / 0.0	8 / 0.0	10 / 0.0	12 / 1.4	9 / 2.9	6 / 4.	5 / 3.9	5 / 2.7	6 / 1.3	6 / .2	6 / 0.0	7 / 0.0
HOMER, AK	50 / 30	5 / 0.0	5 / 0.0	6 / .2	6 / 1.4	7 / 3.2	6 / 4.4	6 / 4.1	5 / 2.8	4 / 1.3	4 / .2	5 / 0.0	4 / 0.0
JUNEAU, AK	62 / 30	4 / 0.0	4 / 0.0	4 / .5	4 / 1.5	4 / 2.9	4 / 4.	4 / 4.	4 / 2.9	4 / 1.4	3 / .4	4 / 0.0	4 / 0.0
PHOENIX, AZ	67 / 30	14 / 0.1	11 / .2	14 / .7	23 / 1.5	34 / 2.4	34 / 3.2	12 / 3.2	12 / 2.4	17 / 1.3	18 / .5	17 / .1	14 / .
TUCSON, AZ	66 / 30	12 / 0.1	13 / .3	12 / .7	17 / 1.5	23 / 2.3	23 / 2.8	7 / 2.8	7 / 2.3	12 / 1.4	14 / .6	17 / .2	12 / .1
WINSLOW, AZ	75 / 30	12 / 1.1	11 / 1.4	12 / 2.2	14 / 3.3	18 / 4.6	17 / 5.9	9 / 5.9	7 / 5.1	10 / 4.	14 / 2.6	14 / 1.4	12 / 1.
YUMA, AZ	45 / 30	14 / 2.0	17 / 2.8	18 / 3.8	23 / 5.3	34 / 6.7	34 / 7.9	23 / 7.3	18 / 6.6	23 / 5.4	23 / 3.9	23 / 2.5	18 / 1.8
FORT SMITH, AR	61 / 30	7 / 2.0	7 / 2.8	6 / 3.8	6 / 5.2	6 / 6.5	6 / 7.6	7 / 7.	7 / 6.1	7 / 5.2	7 / 3.8	7 / 2.5	7 / 1.8
LITTLE ROCK, AR	64 / 30	6 / 1.1	6 / 1.9	6 / 2.9	6 / 4.4	6 / 5.7	6 / 7.1	6 / 6.8	7 / 6.	7 / 4.6	7 / 3.1	6 / 1.8	6 / 1.1
BAKERSFIELD, CA	69 / 30	9 / 2.1	8 / 3.	9 / 4.1	12 / 5.6	23 / 6.8	34 / 7.9	34 / 7.6	34 / 6.8	23 / 5.7	18 / 4.	12 / 2.6	10 / 2.
FRESNO, CA	57 / 30	8 / 1.2	7 / 1.8	8 / 2.9	12 / 4.4	18 / 5.1	34 / 5.8	23 / 6.2	23 / 5.6	23 / 4.4	18 / 3.1	10 / 1.9	8 / 1.2
LONG BEACH, CA	62 / 30	10 / 1.2	10 / 1.8	10 / 2.9	14 / 4.1	23 / 5.1	23 / 5.9	23 / 6.	23 / 5.5	23 / 4.1	18 / 3.1	14 / 1.8	10 / 1.2
LOS ANGELES C.O., CA	66 / 30	9 / 1.5	10 / 2.2	9 / 3.2	14 / 4.5	23 / 5.7	34 / 6.7	23 / 7.2	23 / 6.3	23 / 4.8	18 / 3.3	14 / 1.9	10 / 1.3
SAN DIEGO, CA	66 / 30	9 / 1.2	8 / 2.	9 / 2.9	12 / 4.5	18 / 6.	34 / 7.1	23 / 7.6	34 / 6.6	23 / 5.	18 / 3.3	12 / 1.8	9 / 1.1
SAN FRANCISCO C.O., CA	69 / 30	6 / 1.7	6 / 2.2	6 / 2.7	9 / 3.2	14 / 3.5	23 / 3.8	23 / 3.9	23 / 3.7	17 / 3.2	12 / 2.6	7 / 2.	6 / 1.6
SANTA BARBARA, CA	70 / 30	10 / 1.8	10 / 2.4	9 / 2.9	23 / 3.8	23 / 4.1	34 / 4.7	34 / 5.2	23 / 4.8	23 / 3.9	18 / 2.9	14 / 2.1	10 / 1.7
SANTA MARIA, CA	64 / 30	8 / 0.9	7 / 1.3	8 / 2.	12 / 3.1	23 / 4.4	34 / 5.4	23 / 6.2	23 / 5.5	23 / 3.9	18 / 2.3	10 / 1.1	8 / .7
STOCKTON, CA	64 / 30	7 / 1.1	7 / 1.9	7 / 2.6	10 / 3.8	18 / 5.5	34 / 6.6	23 / 7.4	23 / 6.5	23 / 4.7	14 / 2.9	8 / 1.4	8 / 1.
ALAMOSA, CO	60 / 30	14 / 1.1	11 / 1.8	10 / 2.7	10 / 4.	10 / 5.6	10 / 6.6	7 / 7.1	6 / 6.2	9 / 4.7	12 / 3.1	14 / 1.5	14 / 1.
DENVER, CO	64 / 30	10 / 1.1	10 / 1.7	7 / 2.3	7 / 3.1	6 / 3.7	7 / 4.3	7 / 4.1	7 / 3.8	9 / 3.3	10 / 2.3	10 / 1.4	10 / 1.1
GRAND JUNCTION, CO	60 / 30	9 / 1.1	8 / 1.5	8 / 2.1	9 / 2.7	9 / 3.1	12 / 3.2	12 / 3.2	9 / 2.8	9 / 2.6	10 / 2.1	10 / 1.3	10 / 1.
PUEBLO, CO	64 / 30	12 / 1.8	11 / 2.3	9 / 2.9	9 / 3.7	7 / 4.	8 / 4.3	7 / 4.3	7 / 4.	12 / 3.5	14 / 2.8	14 / 2.1	14 / 1.7
HARTFORD, CT	52 / 30	5 / 1.1	5 / 1.9	5 / 2.8	5 / 4.3	5 / 5.6	5 / 6.7	6 / 7.1	6 / 6.2	6 / 4.7	6 / 3.1	6 / 1.7	5 / 1.
WILMINGTON, DE	59 / 30	6 / 0.6	6 / 1.1	6 / 2.1	5 / 3.3	5 / 4.6	6 / 5.9	6 / 6.	6 / 5.2	6 / 3.9	7 / 2.4	6 / 1.2	6 / .6
DAYTONA BEACH, FL	63 / 30	8 / 1.1	7 / 1.7	8 / 2.6	10 / 4.	8 / 5.2	5 / 6.7	5 / 6.8	5 / 5.9	5 / 4.4	6 / 2.8	8 / 1.5	8 / 1.
FORT MYERS, FL	63 / 30	10 / 0.6	10 / .9	10 / 1.6	12 / 2.6	8 / 3.7	4 / 4.5	4 / 4.6	4 / 4.1	4 / 3.1	8 / 2.	12 / 1.1	12 / .6
GAINESVILLE, FL	23 / 30	6 / 0.6	7 / .9	6 / 1.7	8 / 3.1	7 / 4.5	5 / 5.3	5 / 5.6	4 / 4.8	5 / 3.4	7 / 2.1	7 / 1.1	7 / .6
JACKSONVILLE, FL	65 / 30	6 / 0.7	7 / 1.1	6 / 2.	7 / 3.2	7 / 4.4	5 / 5.2	5 / 5.2	5 / 4.5	5 / 3.4	6 / 2.2	7 / 1.3	7 / .7
KEY WEST, FL	58 / 30	9 / 0.9	10 / 1.2	10 / 2.2	12 / 3.5	8 / 4.8	5 / 5.7	5 / 5.7	5 / 5.	4 / 3.8	6 / 2.4	9 / 1.4	9 / .9
MIAMI, FL	64 / 30	9 / 0.9	8 / 1.2	9 / 2.2	9 / 3.5	6 / 4.5	4 / 5.2	4 / 5.2	4 / 4.6	4 / 3.5	5 / 2.3	7 / 1.3	9 / .9
TALLAHASSEE, FL	45 / 30	6 / 2.7	6 / 3.2	6 / 4.	7 / 5.	6 / 5.5	5 / 5.3	4 / 5.2	5 / 5.	6 / 4.3	8 / 3.5	7 / 3.	6 / 2.6
TAMPA, FL	60 / 30	9 / 2.2	8 / 2.8	9 / 3.8	12 / 5.	10 / 5.6	5 / 5.8	4 / 5.6	4 / 5.2	5 / 4.4	9 / 3.4	10 / 2.6	9 / 2.1
ATHENS, GA	63 / 30	5 / 2.4	6 / 3.	6 / 3.5	6 / 4.1	6 / 4.4	6 / 4.5	6 / 4.6	6 / 4.3	7 / 3.8	7 / 3.2	6 / 2.6	6 / 2.3
ATLANTA, GA	72 / 30	5 / 2.4	5 / 3.1	5 / 4.	6 / 5.	6 / 5.6	6 / 5.6	5 / 5.5	6 / 5.1	7 / 4.4	7 / 3.5	6 / 2.7	6 / 2.3
AUGUSTA,GA	56 / 30	6 / 1.7	6 / 2.3	6 / 3.2	7 / 4.1	6 / 4.9	6 / 5.3	5 / 5.1	6 / 4.8	7 / 4.	7 / 3.3	7 / 2.2	6 / 1.7
MACON, GA	58 / 30	6 / 2.3	6 / 2.9	6 / 3.8	7 / 4.7	6 / 5.4	6 / 5.3	5 / 5.1	6 / 4.9	7 / 4.3	8 / 3.5	7 / 2.7	6 / 2.2
HILO, HI	64 / 30	4 / 2.6	4 / 3.1	3 / 3.8	3 / 4.5	3 / 4.8	3 / 5.	3 / 5.	3 / 4.8	3 / 4.	3 / 3.3	3 / 2.6	4 / 2.3
HONOLULU,HI	57 / 30	7 / 1.3	7 / 2.	7 / 3.1	7 / 4.3	9 / 5.1	10 / 5.7	8 / 5.6	10 / 5.	9 / 4.	7 / 2.9	6 / 1.9	7 / 1.3
KAHULUI, HI	48 / 30	6 / 1.3	6 / 1.9	6 / 2.9	6 / 4.1	9 / 4.9	10 / 5.4	9 / 5.4	9 / 4.9	12 / 3.9	9 / 2.8	6 / 1.9	6 / 1.3
LIHUE, HI	56 / 30	5 / 1.6	4 / 2.2	4 / 3.4	4 / 4.7	4 / 5.6	4 / 6.1	3 / 6.	4 / 5.4	4 / 4.4	4 / 3.3	4 / 2.2	4 / 1.6
BOISE, ID	67 / 30	6 / 1.6	6 / 2.3	7 / 3.3	7 / 4.6	8 / 5.4	10 / 6.	18 / 5.7	18 / 5.2	14 / 4.3	10 / 3.3	6 / 2.1	6 / 1.6
POCATELLO, ID	57 / 30	5 / 1.6	6 / 2.3	7 / 3.4	7 / 4.7	7 / 5.6	9 / 6.1	12 / 6.	12 / 5.4	12 / 4.5	10 / 3.3	7 / 2.2	6 / 1.6

CHICAGO,IL	48 / 30	6 / 1.7	6 / 2.3	5 / 3.3	5 / 4.5	6 / 5.2	6 / 5.7	7 / 5.6	7 / 5.	6 / 4.	7 / 3.2	6 / 2.2	6 / 1.7
MOLINE, IL	74 / 30	7 / 3.1	7 / 3.4	6 / 3.8	5 / 4.	6 / 4.3	6 / 4.5	7 / 4.4	7 / 4.4	7 / 4.1	8 / 3.7	7 / 3.1	7 / 2.8
SPRINGFIELD, IL	59 / 30	7 / 2.6	7 / 3.	6 / 3.3	5 / 3.7	6 / 3.9	6 / 3.9	7 / 3.9	7 / 3.9	8 / 3.7	8 / 3.1	6 / 2.5	7 / 2.3
EVANSVILLE, IN	66 / 30	6 / 0.6	6 / 1.	5 / 2.	5 / 3.2	5 / 4.6	6 / 5.8	6 / 6.7	7 / 5.6	7 / 3.7	7 / 2.1	6 / .9	6 / .5
INDIANAPOLIS, IN	67 / 30	6 / 0.5	6 / .9	5 / 1.7	5 / 3.	5 / 4.4	6 / 5.7	7 / 6.6	7 / 5.7	8 / 3.7	7 / 2.1	6 / .8	6 / .5
DES MOINES, IA	67 / 30	8 / 0.5	7 / .8	7 / 1.6	6 / 3.	6 / 4.3	6 / 5.2	7 / 5.4	7 / 4.5	7 / 3.3	8 / 2.	8 / .9	8 / .5
SIOUX CITY, IA	66 / 30	9 / 0.5	8 / .8	7 / 1.7	6 / 3.2	6 / 4.5	6 / 5.6	7 / 5.5	7 / 4.8	7 / 3.4	9 / 2.1	10 / .9	9 / .5
WATERLOO, IA	56 / 30	8 / 0.5	8 / .9	7 / 1.7	6 / 3.2	6 / 4.5	6 / 5.4	7 / 5.4	7 / 4.6	7 / 3.5	8 / 2.2	8 / 1.1	8 / .5
CONCORDIA, KS	44 / 30	10 / 0.4	11 / .7	8 / 1.5	6 / 3.	6 / 4.4	6 / 5.3	7 / 5.4	7 / 4.5	8 / 3.3	9 / 2.	10 / .9	12 / .5
DODGE CITY, KS	64 / 30	12 / 0.6	11 / 1.	9 / 1.8	9 / 3.3	7 / 4.6	7 / 5.6	7 / 5.5	7 / 4.8	9 / 3.7	10 / 2.3	12 / 1.2	12 / .6
GOODLAND, KS	86 / 30	12 / 0.9	11 / 1.2	9 / 2.3	8 / 3.7	7 / 4.9	6 / 5.8	7 / 5.7	8 / 5.1	10 / 3.9	12 / 2.6	12 / 1.4	14 / .9
TOPEKA, KS	60 / 30	9 / 0.5	8 / .8	7 / 1.7	6 / 3.1	6 / 4.4	6 / 5.3	7 / 5.4	7 / 4.6	8 / 3.4	8 / 2.1	9 / .9	10 / .5
WICHITA, KS	53 / 30	10 / 0.6	10 / 1.	8 / 2.	8 / 3.3	6 / 4.5	6 / 5.4	8 / 5.4	8 / 4.8	8 / 3.7	9 / 2.2	10 / 1.2	10 / .6
JACKSON, KY	26 / 30	5 / 0.5	5 / .8	5 / 1.7	5 / 3.2	5 / 4.5	5 / 5.3	5 / 5.5	6 / 4.8	6 / 3.4	6 / 2.1	5 / .9	5 / .5
LOUISVILLE, KY	59 / 30	5 / 0.4	5 / .8	5 / 1.6	5 / 3.3	5 / 4.5	6 / 5.4	6 / 5.6	6 / 4.8	7 / 3.4	7 / 2.1	6 / .9	5 / .5
PADUCAH KY	23 / 30	6 / 0.4	6 / .7	6 / 1.5	5 / 3.1	5 / 4.4	6 / 5.4	6 / 5.4	7 / 4.6	7 / 3.3	6 / 2.	6 / .8	6 / .4
BATON ROUGE, LA	55 / 30	6 / 0.7	6 / 1.1	6 / 2.1	7 / 3.4	7 / 4.5	6 / 5.8	5 / 6.1	5 / 5.2	6 / 3.8	8 / 2.4	7 / 1.2	6 / .7
LAKE CHARLES, LA	45 / 30	6 / 1.0	6 / 1.4	7 / 2.4	7 / 3.9	7 / 4.9	6 / 6.	6 / 6.5	6 / 5.6	6 / 4.	7 / 2.7	7 / 1.4	6 / .9
NEW ORLEANS, LA	58 / 30	6 / 2.1	6 / 2.4	6 / 3.1	7 / 3.8	7 / 4.1	5 / 4.7	5 / 5.4	5 / 5.4	6 / 5.	7 / 4.	7 / 2.8	6 / 2.1
SHREVEPORT, LA	54 / 30	6 / 0.7	6 / 1.2	6 / 2.3	6 / 3.7	6 / 4.8	6 / 5.6	7 / 5.7	7 / 5.1	7 / 3.9	7 / 2.6	6 / 1.3	6 / .7
PORTLAND, ME	66 / 30	5 / 0.7	6 / 1.1	5 / 2.1	5 / 3.4	5 / 4.6	5 / 5.4	6 / 5.4	6 / 4.9	6 / 3.7	6 / 2.3	5 / 1.2	5 / .7
BALTIMORE, MD	56 / 30	6 / 0.9	6 / 1.3	6 / 2.3	6 / 3.5	6 / 4.5	6 / 5.1	7 / 5.1	7 / 4.6	8 / 3.5	8 / 2.3	7 / 1.4	7 / .9
BLUE HILL, MA	121 / 30	5 / 0.9	5 / 1.2	5 / 2.2	5 / 3.5	5 / 4.5	5 / 5.4	6 / 5.4	6 / 4.9	6 / 3.7	6 / 2.3	6 / 1.3	5 / .9
WORCESTER, MA	51 / 30	5 / 0.9	5 / 1.3	5 / 2.4	5 / 3.7	5 / 4.8	5 / 5.7	6 / 5.6	6 / 5.1	6 / 3.9	6 / 2.7	5 / 1.4	5 / 1.
GRAND RAPIDS, MI	43 / 30	4 / 1.6	5 / 2.2	5 / 3.3	5 / 4.5	6 / 5.2	6 / 5.8	7 / 6.	7 / 5.6	6 / 4.5	6 / 3.3	5 / 2.1	4 / 1.6
LANSING, MI	52 / 30	5 / 0.5	5 / .8	5 / 1.3	5 / 2.5	6 / 3.7	6 / 4.6	7 / 4.9	7 / 4.1	6 / 3.	7 / 1.7	5 / .8	5 / .5
DULUTH, MN	65 / 30	6 / 0.6	6 / .9	6 / 1.5	6 / 2.5	5 / 3.7	5 / 4.6	6 / 4.8	6 / 4.	5 / 3.	7 / 1.8	6 / .9	6 / .6
ROCHESTER, MN	46 / 30	7 / 0.5	7 / .8	6 / 1.6	5 / 2.8	5 / 4.3	5 / 5.2	6 / 5.4	7 / 4.6	6 / 3.3	7 / 2.	6 / .9	7 / .5
SAINT CLOUD, MN	66 / 30	7 / 0.4	8 / .7	7 / 1.5	6 / 2.7	6 / 4.1	5 / 5.1	6 / 5.2	7 / 4.4	6 / 3.1	8 / 1.7	8 / .8	7 / .5
JACKSON, MS	43 / 30	6 / 0.4	6 / .7	6 / 1.5	6 / 2.8	6 / 4.3	6 / 5.3	6 / 5.4	6 / 4.5	7 / 3.2	7 / 1.8	6 / .8	6 / .5
MERIDIAN, MS	61 / 30	6 / 0.4	6 / .6	6 / 1.2	6 / 2.5	6 / 4.	6 / 5.1	5 / 5.2	6 / 4.3	7 / 2.8	8 / 1.6	6 / .7	6 / .4
TUPELO, MS	23 / 30	6 / 0.4	5 / .7	6 / 1.5	6 / 2.8	6 / 4.3	6 / 5.3	6 / 5.5	7 / 4.6	7 / 3.2	7 / 1.8	6 / .8	6 / .5
COLUMBIA, MO	37 / 30	8 / 0.4	7 / .7	6 / 1.3	5 / 2.6	5 / 4.	7 / 4.8	7 / 5.	7 / 4.1	7 / 3.	7 / 1.7	6 / .8	7 / .4
ST. LOUIS, MO	49 / 30	7 / 0.2	7 / .4	6 / 1.	5 / 2.1	6 / 3.8	6 / 4.7	7 / 5.	7 / 4.	8 / 2.7	7 / 1.3	6 / .6	7 / .2
SPRINGFIELD, MO	61 / 30	6 / 0.1	6 / .3	6 / 1.	6 / 2.1	5 / 3.7	6 / 4.6	6 / 4.9	6 / 3.9	7 / 2.5	6 / 1.3	6 / .5	6 / .2
BILLINGS, MT	72 / 30	8 / 0.0	7 / .2	7 / 1.	6 / 2.4	6 / 3.9	5 / 4.8	8 / 5.1	9 / 4.1	8 / 2.5	9 / 1.2	9 / .5	9 / .1
GREAT FALLS, MT	69 / 30	7 / 0.2	7 / .6	7 / 1.2	6 / 2.7	6 / 4.1	5 / 5.1	8 / 5.2	8 / 4.4	8 / 3.	9 / 1.7	9 / .7	8 / .2
HELENA, MT	66 / 30	8 / 0.1	8 / .4	7 / 1.2	7 / 2.7	6 / 4.3	5 / 5.3	8 / 5.5	8 / 4.5	9 / 3.	10 / 1.6	9 / .6	8 / .2
MISSOULA, MT	62 / 30	5 / 1.7	6 / 2.3	6 / 3.4	6 / 4.7	6 / 5.5	5 / 6.1	8 / 6.	8 / 5.6	8 / 4.6	7 / 3.4	5 / 2.2	5 / 1.7
GRAND ISLAND, NE	68 / 30	10 / 1.2	10 / 1.9	8 / 2.9	7 / 4.3	6 / 5.	6 / 5.8	7 / 5.7	8 / 5.2	8 / 4.3	10 / 3.1	12 / 1.9	12 / 1.2
LINCOLN, NE	35 / 30	10 / 0.7	10 / 1.1	7 / 2.1	6 / 3.5	6 / 4.5	6 / 5.4	7 / 5.9	7 / 5.1	8 / 3.7	9 / 2.3	9 / 1.3	10 / .7
NORFOLK, NE	61 / 30	10 / 0.6	10 / 1.1	8 / 2.1	6 / 3.4	6 / 4.5	6 / 5.3	7 / 5.6	7 / 4.9	8 / 3.7	10 / 2.3	10 / 1.2	10 / .7
NORTH PLATTE, NE	54 / 30	12 / 0.7	10 / 1.2	9 / 2.2	7 / 3.5	6 / 4.6	6 / 5.4	7 / 5.5	7 / 4.9	9 / 3.7	10 / 2.3	12 / 1.3	14 / .7
OMAHA (NORTH), NE	18 / 30	10 / 0.5	8 / .9	6 / 1.6	5 / 2.8	5 / 4.	6 / 5.3	6 / 6.1	7 / 5.1	6 / 3.2	8 / 1.7	9 / .7	8 / .4
SCOTTSBLUFF, NE	63 / 30	10 / 0.1	10 / .4	8 / 1.2	7 / 2.7	6 / 4.1	6 / 5.3	7 / 5.9	9 / 5.	9 / 3.	10 / 1.6	12 / .6	10 / .2
VALENTINE, NE	51 / 30	12 / 0.4	11 / .8	9 / 1.5	7 / 2.7	6 / 4.	6 / 5.1	7 / 5.9	8 / 4.9	9 / 3.	10 / 1.6	12 / .7	12 / .4
ELY, NV	68 / 30	9 / 0.4	7 / .8	7 / 1.5	8 / 2.8	8 / 4.	12 / 5.3	10 / 6.1	10 / 5.1	12 / 3.1	12 / 1.7	10 / .7	9 / .4
LAS VEGAS, NV	58 / 30	14 / 0.4	13 / .7	14 / 1.3	23 / 2.7	23 / 3.9	34 / 5.	18 / 5.7	18 / 4.9	23 / 3.	23 / 1.5	23 / .5	18 / .2
RENO, NV	64 / 30	9 / 0.4	8 / .8	9 / 1.6	12 / 3.	12 / 4.1	14 / 5.2	18 / 6.1	18 / 5.1	17 / 3.2	18 / 1.6	12 / .6	9 / .4
WINNEMUCCA, NV	57 / 30	7 / 0.6	7 / 1.	8 / 2.	9 / 3.4	9 / 4.6	12 / 5.8	18 / 5.9	18 / 5.1	14 / 3.7	12 / 2.3	8 / 1.1	7 / .6
CONCORD, NH	65 / 30	6 / 0.6	6 / 1.	6 / 2.	5 / 3.5	5 / 4.8	5 / 5.8	6 / 6.	7 / 5.1	6 / 3.7	7 / 2.3	5 / 1.2	6 / .6

NEWARK, NJ	65 / 30	6 / 0.6	6 / 1.1	5 / 2.	5 / 3.4	5 / 4.6	6 / 5.8	6 / 6.1	6 / 5.4	6 / 3.9	6 / 2.3	6 / 1.2	6 / .6
ALBUQUERQUE, NM	67 / 30	14 / 0.5	11 / .9	12 / 1.8	14 / 3.4	12 / 4.6	14 / 5.7	7 / 5.7	7 / 4.9	10 / 3.5	12 / 2.2	14 / 1.1	12 / .5
CLAYTON, NM	57 / 30	14 / 0.5	13 / .9	12 / 1.7	10 / 3.2	8 / 4.4	8 / 5.3	7 / 5.4	7 / 4.6	10 / 3.3	14 / 2.1	14 / .9	14 / .5
ROSWELL, NM	34 / 30	14 / 0.7	13 / 1.2	14 / 2.	17 / 3.4	12 / 4.6	12 / 5.9	9 / 6.6	7 / 5.6	9 / 3.9	12 / 2.3	14 / 1.1	14 / .6
ALBANY, NY	60 / 30	5 / 0.5	6 / .9	5 / 1.7	5 / 3.2	5 / 4.6	5 / 5.9	6 / 6.3	6 / 5.4	6 / 3.7	7 / 2.2	5 / .9	5 / .5
BINGHAMTON, NY	55 / 30	4 / 0.7	4 / 1.2	4 / 2.	5 / 3.3	5 / 4.6	5 / 6.	6 / 7.1	6 / 6.1	6 / 4.3	6 / 2.4	4 / 1.1	4 / .6
BUFFALO, NY	63 / 30	3 / 0.9	4 / 1.3	4 / 2.	4 / 3.2	5 / 4.5	6 / 5.9	6 / 6.7	6 / 5.7	5 / 4.	6 / 2.4	4 / 1.2	3 / .7
SYRACUSE, NY	57 / 30	3 / 0.9	4 / 1.2	4 / 2.1	4 / 3.2	5 / 4.4	5 / 5.2	6 / 5.2	6 / 4.6	5 / 3.5	5 / 2.3	4 / 1.3	4 / .9
CHARLOTTE, NC	67 / 30	6 / 1.2	6 / 1.9	6 / 2.9	6 / 4.4	6 / 5.6	6 / 6.7	5 / 6.6	6 / 5.6	7 / 4.4	7 / 2.9	7 / 1.7	6 / 1.1
RALEIGH, NC	62 / 30	6 / 1.6	6 / 2.3	6 / 3.4	6 / 4.8	6 / 6.	6 / 7.1	5 / 6.7	6 / 6.	7 / 4.7	7 / 3.4	6 / 2.2	6 / 1.6
WILMINGTON, NC	55 / 30	6 / 0.5	6 / .8	6 / 1.6	7 / 3.	6 / 4.4	6 / 5.4	5 / 5.6	5 / 4.8	6 / 3.3	7 / 2.	7 / .9	6 / .5
BISMARCK, ND	67 / 30	8 / 0.4	8 / .7	7 / 1.3	8 / 2.5	7 / 3.8	5 / 4.6	7 / 4.8	7 / 4.	8 / 2.8	10 / 1.7	9 / .8	8 / .5
FARGO, ND	64 / 30	7 / 0.5	7 / .7	8 / 1.3	7 / 2.6	6 / 3.8	6 / 4.6	7 / 4.8	7 / 4.	7 / 3.	9 / 1.7	9 / .8	7 / .5
WILLISTON, ND	45 / 30	7 / 0.6	8 / .9	8 / 1.6	7 / 2.7	7 / 3.8	5 / 4.5	7 / 4.5	8 / 4.	9 / 2.7	10 / 2.	9 / 1.1	7 / .7
AKRON, OH	58 / 30	4 / 0.6	4 / 1.	4 / 1.7	4 / 3.	5 / 4.1	5 / 4.8	6 / 5.	7 / 4.3	6 / 3.1	6 / 2.	5 / 1.1	4 / .6
COLUMBUS, OH	67 / 30	5 / 0.6	5 / .9	5 / 1.6	5 / 2.7	5 / 3.8	5 / 4.6	6 / 4.6	7 / 4.	7 / 3.	7 / 1.8	5 / .9	5 / .6
DAYTON, OH	63 / 30	5 / 0.5	6 / .7	5 / 1.5	5 / 2.7	5 / 4.	6 / 5.	6 / 5.1	7 / 4.3	7 / 3.1	7 / 1.8	5 / .8	6 / .5
MANSFIELD, OH	47 / 30	5 / 0.5	5 / .8	5 / 1.5	5 / 2.7	5 / 4.1	5 / 5.1	6 / 5.2	6 / 4.4	6 / 3.1	7 / 1.8	5 / .8	5 / .5
OKLAHOMA CITY, OK	67 / 30	10 / 1.2	8 / 1.8	8 / 2.8	8 / 4.	7 / 4.9	7 / 5.6	9 / 5.5	9 / 4.9	8 / 3.9	9 / 2.7	10 / 1.8	10 / 1.2
TULSA, OK	67 / 30	9 / 1.1	8 / 1.7	7 / 2.7	7 / 3.9	6 / 4.9	6 / 5.4	9 / 5.5	9 / 4.9	8 / 3.8	9 / 2.7	9 / 1.7	9 / 1.1
ASTORIA, OR	53 / 30	3 / 1.2	4 / 1.8	4 / 2.8	4 / 4.1	5 / 5.	5 / 5.6	7 / 5.5	7 / 4.9	6 / 3.9	4 / 2.8	4 / 1.8	3 / 1.2
EUGENE, OR	64 / 30	4 / 1.5	4 / 2.	4 / 3.1	5 / 4.3	6 / 5.1	7 / 5.2	10 / 5.2	9 / 4.8	8 / 4.1	5 / 3.1	4 / 2.1	4 / 1.5
MEDFORD, OR	77 / 30	5 / 0.1	5 / .4	6 / 1.2	6 / 2.7	7 / 4.3	12 / 5.3	23 / 5.9	23 / 5.	14 / 3.1	8 / 1.7	5 / .6	5 / .2
PENDLETON, OR	71 / 30	5 / 0.1	6 / .3	6 / 1.	6 / 2.6	7 / 4.3	9 / 5.2	18 / 5.5	18 / 4.6	12 / 3.	8 / 1.6	5 / .6	5 / .1
GUAM, PC	49 / 30	4 / 0.1	4 / .4	4 / 1.2	4 / 2.7	4 / 4.3	3 / 5.4	3 / 5.9	3 / 5.	3 / 3.1	3 / 1.6	3 / .6	3 / .2
JOHNSTON ISLAND, PC	28 / 30	6 / 0.5	5 / .8	4 / 1.7	4 / 3.	5 / 4.1	5 / 5.1	5 / 5.2	5 / 4.4	4 / 3.2	4 / 2.	4 / .9	4 / .5
KOROR, PC	55 / 30	3 / 0.6	4 / 1.	4 / 2.	4 / 3.2	3 / 4.5	3 / 5.3	3 / 5.4	4 / 4.6	4 / 3.5	3 / 2.2	3 / 1.1	3 / .6
KWAJALEIN, MARSH. IS., PC	54 / 30	5 / 0.6	5 / 1.	5 / 2.	4 / 3.2	4 / 4.4	3 / 5.4	3 / 5.5	3 / 4.8	3 / 3.5	3 / 2.2	3 / 1.1	4 / .6
MAJURO, MARSHALL IS, PC	52 / 30	4 / 0.5	4 / .9	4 / 1.7	4 / 3.	3 / 4.1	3 / 5.1	3 / 5.1	3 / 4.4	3 / 3.2	3 / 2.	3 / .9	3 / .6
PAGO PAGO, AM. SAM., PC	40 / 30	3 / 0.5	3 / .8	3 / 1.6	4 / 3.1	4 / 4.4	4 / 5.4	4 / 5.5	4 / 4.6	4 / 3.4	4 / 2.	4 / .9	3 / .5
POHNPEI, CAROLINE IS., PC	55 / 30	3 / 0.5	4 / .8	3 / 1.6	3 / 3.	3 / 4.3	3 / 5.1	3 / 5.2	3 / 4.5	3 / 3.2	3 / 2.	3 / .9	3 / .5
CHUUK, E. CAROLINE IS., PC	55 / 30	4 / 1.1	4 / 1.8	4 / 2.8	4 / 4.	3 / 4.9	3 / 5.7	3 / 6.2	3 / 5.6	3 / 4.1	3 / 2.8	3 / 1.7	3 / 1.1
WAKE ISLAND, PC	50 / 30	6 / 1.1	6 / 1.7	5 / 2.8	4 / 4.1	4 / 4.9	4 / 5.7	3 / 6.	3 / 5.5	3 / 4.	3 / 2.8	4 / 1.7	5 / 1.1
YAP, W CAROLINE IS., PC	58 / 30	4 / 0.6	4 / 1.1	4 / 1.7	4 / 2.5	4 / 3.2	3 / 3.5	3 / 3.7	3 / 3.3	3 / 2.7	3 / 1.6	3 / .8	3 / .5
ERIE, PA.	53 / 30	4 / 0.6	4 / 1.2	5 / 2.	4 / 3.	5 / 4.	6 / 5.	7 / 5.7	6 / 5.	6 / 3.5	5 / 2.	4 / .8	4 / .6
PITTSBURGH, PA	54 / 30	4 / 0.7	4 / 1.4	4 / 2.3	5 / 3.5	5 / 4.9	5 / 6.	6 / 6.8	7 / 6.	6 / 4.3	6 / 2.4	5 / 1.1	4 / .6
AVOCA, PA	51 / 30	5 / 0.6	6 / .9	5 / 1.5	5 / 2.4	5 / 3.4	5 / 4.3	6 / 4.8	6 / 4.1	6 / 3.	7 / 1.6	5 / .7	5 / .5
PROVIDENCE, RI	53 / 30	5 / 3.2	6 / 3.5	5 / 4.	5 / 4.4	5 / 4.5	6 / 4.4	6 / 4.4	6 / 4.3	6 / 4.3	6 / 3.8	6 / 3.3	5 / 3.1
CHARLESTON AP,SC	64 / 30	7 / 3.5	7 / 3.9	7 / 4.1	8 / 4.3	7 / 4.1	5 / 4.	5 / 3.9	5 / 4.	6 / 4.	9 / 3.9	8 / 3.8	7 / 3.5
COLUMBIA, SC	59 / 30	6 / 3.1	6 / 3.4	6 / 3.7	6 / 3.7	6 / 3.7	6 / 3.5	5 / 3.7	6 / 3.8	7 / 3.8	7 / 3.5	7 / 3.2	6 / 2.9
GREENVIL-SPART AP, SC	44 / 30	6 / 3.1	6 / 3.3	6 / 3.5	6 / 3.5	6 / 3.5	6 / 3.5	5 / 3.5	6 / 3.7	6 / 3.7	7 / 3.5	6 / 3.3	6 / 3.1
ABERDEEN, SD	75 / 30	9 / 4.3	8 / 4.2	8 / 3.9	7 / 3.4	7 / 2.8	6 / 2.5	7 / 2.6	7 / 2.9	9 / 3.4	10 / 3.7	10 / 4.	9 / 4.1
HURON, SD	67 / 30	10 / 3.5	8 / 3.7	8 / 4.	7 / 4.1	6 / 4.1	6 / 4.1	7 / 4.4	7 / 4.5	9 / 4.5	10 / 4.4	10 / 4.	10 / 3.5
RAPID CITY, SD	64 / 30	9 / 3.2	8 / 3.3	7 / 3.5	6 / 3.8	6 / 3.8	5 / 3.8	7 / 3.9	8 / 4.	9 / 4.	10 / 3.9	10 / 3.5	10 / 3.2
SIOUX FALLS, SD	61 / 30	9 / 2.6	8 / 2.9	7 / 3.4	6 / 3.8	6 / 4.	5 / 4.1	7 / 4.1	7 / 4.	7 / 3.8	9 / 3.3	9 / 2.7	9 / 2.4
CHATTANOOGA, TN	76 / 30	5 / 3.4	5 / 3.6	5 / 4.	6 / 4.3	6 / 4.1	6 / 4.	5 / 4.	6 / 4.1	6 / 4.1	7 / 3.9	6 / 3.5	6 / 3.3
KNOXVILLE, TN	64 / 30	5 / 0.5	5 / .8	5 / 1.5	6 / 2.5	5 / 3.8	6 / 4.6	5 / 4.6	6 / 4.	6 / 2.8	7 / 1.7	6 / .8	6 / .5
MEMPHIS, TN	56 / 30	6 / 0.6	6 / 1.	6 / 1.8	6 / 3.2	6 / 4.4	6 / 5.2	6 / 5.4	7 / 4.6	7 / 3.4	7 / 2.1	6 / 1.1	6 / .6
NASHVILLE, TN	65 / 30	5 / 0.6	5 / 1.	5 / 1.8	6 / 3.2	5 / 4.4	6 / 5.2	6 / 5.4	6 / 4.6	7 / 3.4	7 / 2.1	6 / 1.1	6 / .6
ABILENE, TX	67 / 30	12 / 0.7	10 / 1.1	12 / 2.	10 / 3.2	8 / 4.4	9 / 5.2	12 / 5.2	10 / 4.6	10 / 3.4	10 / 2.2	12 / 1.2	12 / .7
AMARILLO, TX	65 / 30	12 / 0.6	11 / .9	12 / 1.8	10 / 3.1	7 / 4.4	7 / 5.2	8 / 5.2	7 / 4.5	10 / 3.3	12 / 2.1	14 / 1.1	12 / .6
AUSTIN, TX	65 / 30	8 / 0.5	7 / .8	8 / 1.6	8 / 2.8	7 / 4.1	9 / 5.	12 / 5.1	10 / 4.4	9 / 3.2	9 / 1.8	8 / .9	8 / .5

CORPUS CHRISTI, TX	67 / 30	8 / 0.6	8 / .9	10 / 1.7	12 / 3.1	9 / 4.4	9 / 5.2	12 / 5.4	10 / 4.5	6 / 3.3	9 / 2.	10 / 1.1	9 / .6
DALLAS-FORT WORTH, TX	53 / 30	9 / 0.6	8 / .9	8 / 1.6	8 / 2.8	7 / 3.9	9 / 4.8	12 / 5.	12 / 4.4	9 / 3.3	9 / 2.1	9 / 1.1	9 / .6
EL PASO, TX	67 / 30	14 / 1.6	13 / 2.2	18 / 3.2	23 / 4.3	18 / 5.	14 / 5.4	8 / 5.4	8 / 4.9	10 / 3.9	12 / 3.1	17 / 2.2	14 / 1.6
GALVESTON, TX	63 / 30	6 / 1.6	7 / 2.2	7 / 3.3	9 / 4.6	9 / 5.6	8 / 6.	7 / 6.	7 / 5.2	6 / 4.3	8 / 3.2	7 / 2.1	6 / 1.6
HOUSTON, TX	37 / 30	6 / 1.2	7 / 1.9	7 / 2.9	9 / 4.1	7 / 5.1	6 / 5.6	7 / 5.5	7 / 4.9	7 / 3.9	8 / 2.8	7 / 1.8	7 / 1.2
LUBBOCK, TX	60 / 30	14 / 0.2	11 / .6	12 / 1.3	12 / 2.8	8 / 4.4	8 / 5.3	9 / 5.9	9 / 5.1	10 / 3.3	10 / 1.8	14 / .7	14 / .2
MIDLAND-ODESSA, TX	59 / 30	14 / 0.2	13 / .7	18 / 1.5	14 / 3.	10 / 4.5	12 / 5.6	12 / 5.9	10 / 5.	10 / 3.4	12 / 2.	14 / .8	14 / .4
PORT ARTHUR, TX	53 / 30	6 / 0.5	6 / .9	7 / 1.7	7 / 3.	7 / 4.3	6 / 5.4	5 / 6.	5 / 5.2	6 / 3.5	7 / 2.	7 / .9	6 / .5
SAN ANGELO, TX	59 / 30	12 / 0.4	11 / .7	12 / 1.5	12 / 3.1	9 / 4.5	10 / 5.6	12 / 5.7	10 / 4.9	10 / 3.3	10 / 2.	12 / .8	14 / .4
SAN ANTONIO, TX	64 / 30	8 / 1.0	7 / 1.5	8 / 2.6	9 / 3.8	7 / 4.8	9 / 5.4	12 / 5.4	10 / 4.9	9 / 3.9	9 / 2.7	9 / 1.5	8 / 1.1
VICTORIA, TX	45 / 30	7 / 1.1	7 / 1.8	8 / 2.8	9 / 4.1	8 / 5.	7 / 5.8	8 / 5.6	7 / 5.1	6 / 3.9	8 / 2.8	9 / 1.8	7 / 1.2
WACO, TX	63 / 30	8 / 1.1	7 / 1.7	8 / 2.8	8 / 4.	7 / 5.	9 / 5.7	12 / 5.6	10 / 5.1	9 / 4.	9 / 2.7	9 / 1.7	9 / 1.1
WICHITA FALLS, TX	63 / 30	12 / 1.2	10 / 1.8	9 / 2.8	9 / 4.	7 / 4.9	9 / 5.8	10 / 5.7	10 / 5.2	9 / 4.	9 / 2.9	10 / 1.8	12 / 1.2
BURLINGTON, VT	63 / 30	5 / 1.1	5 / 1.7	5 / 2.7	5 / 4.	5 / 5.	5 / 5.7	5 / 5.7	5 / 5.1	5 / 4.	6 / 2.8	4 / 1.7	5 / 1.1
LYNCHBURG, VA	62 / 30	6 / 1.6	6 / 2.2	6 / 3.4	6 / 4.6	5 / 5.5	6 / 6.1	5 / 6.3	6 / 5.9	6 / 4.4	7 / 3.3	6 / 2.1	6 / 1.6
NORFOLK, VA	58 / 30	6 / 1.3	6 / 1.9	6 / 2.9	6 / 4.4	6 / 5.4	6 / 6.3	5 / 6.3	6 / 5.6	6 / 4.3	7 / 2.9	6 / 1.8	6 / 1.2
ROANOKE, VA	59 / 30	6 / 1.8	6 / 2.4	6 / 3.4	6 / 4.4	5 / 5.	6 / 5.8	5 / 6.1	6 / 5.7	6 / 4.7	7 / 3.5	6 / 2.5	6 / 1.8
OLYMPIA, WA	65 / 30	4 / 2.3	4 / 3.0	4 / 3.9	5 / 4.6	5 / 4.9	6 / 5.3	9 / 5.5	8 / 5.4	6 / 4.5	5 / 3.8	4 / 2.8	4 / 2.3
QUILLAYUTE, WA	40 / 30	3 / 2.1	4 / 2.8	4 / 3.8	4 / 4.5	4 / 5.	5 / 5.3	6 / 5.6	6 / 5.4	5 / 4.5	4 / 3.7	3 / 2.7	3 / 2.1
SPOKANE, WA	59 / 30	5 / 1.5	6 / 2.1	6 / 3.2	6 / 4.4	7 / 5.1	8 / 6.1	12 / 6.3	12 / 5.9	10 / 4.5	8 / 3.2	5 / 2.	5 / 1.5
YAKIMA, WA	60 / 30	7 / 2.1	7 / 2.8	9 / 3.9	10 / 5.1	10 / 5.6	12 / 6.1	18 / 6.3	18 / 6.	14 / 4.7	10 / 3.5	7 / 2.5	7 / 2.
SAN JUAN, PR	51 / 30	4 / 1.7	4 / 2.4	5 / 3.7	5 / 5.	4 / 6.2	4 / 7.3	3 / 6.8	4 / 6.1	4 / 4.7	4 / 3.5	4 / 2.2	3 / 1.7
CHARLESTON, WV	59 / 30	5 / 1.5	5 / 1.9	5 / 2.4	5 / 3.	5 / 3.3	5 / 3.7	5 / 3.8	6 / 3.5	6 / 3.1	6 / 2.4	5 / 1.8	5 / 1.5
HUNTINGTON, WV	45 / 30	5 / 1.5	5 / 2.2	5 / 3.3	5 / 4.6	5 / 5.6	5 / 6.3	5 / 6.2	6 / 5.5	6 / 4.3	6 / 3.2	5 / 2.	5 / 1.5
GREEN BAY, WI	57 / 30	6 / 1.8	7 / 2.4	6 / 3.4	6 / 4.3	6 / 5.	6 / 5.4	7 / 5.6	6 / 5.2	6 / 4.3	7 / 3.4	6 / 2.4	6 / 1.8
LA CROSSE, WI	54 / 30	7 / 1.7	7 / 2.4	7 / 3.8	6 / 5.1	6 / 6.	5 / 6.6	6 / 6.8	7 / 6.2	6 / 4.6	7 / 3.4	7 / 2.4	7 / 1.7
MADISON, WI	58 / 30	6 / 2.0	7 / 2.6	6 / 3.7	5 / 4.7	6 / 5.2	6 / 5.8	6 / 6.	7 / 5.7	6 / 4.6	7 / 3.7	6 / 2.5	7 / 2.
CASPER, WY	56 / 30	9 / 2.0	7 / 2.6	7 / 3.7	6 / 4.5	6 / 5.	7 / 5.6	8 / 5.7	10 / 5.5	9 / 4.5	9 / 3.5	9 / 2.6	9 / 2.1
LANDER, WY	60 / 30	12 / 1.5	10 / 2.1	8 / 3.2	7 / 4.5	7 / 5.5	9 / 6.3	10 / 6.7	12 / 6.	10 / 4.5	10 / 3.2	10 / 2.	12 / 1.5
SHERIDAN, WY	66 / 30	7 / 0.6	7 / 1.1	6 / 2.1	6 / 3.2	6 / 4.6	6 / 5.9	8 / 6.6	9 / 5.6	8 / 3.9	8 / 2.3	8 / 1.1	7 / .6
ALGERIES CITY, ALGERIA	1 / 1	4 / 1.0	6 / 1.5	4 / 1.9	12 / 2.4	6 / 3.7	12 / 4.8	10 / 5.0	10 / 4.6	6 / 3.5	5 / 2.4	3 / 1.6	4 / 1.3

Conclusion

The mid- and end-season default crop coefficient values in FAO-56 were developed for a climate that has an average wind speed of 4 ½ mph (2 m/s) and an average minimum relative humidity value of 45%. If the climate of a local region deviates very much from these values then the “off-the-shelf crop coefficient values” from FAO-56 may be causing over- or under-irrigation.

The initial crop coefficient for the single coefficient procedure (K_{c_ini}), which is the method normally used in computer program, is influenced by interval between wetting events. The default FAO-56 values w3ere based on approximately a 10-day interval. If rainfall/irrigation events occur more frequently then this the default FAO-56 values can greatly underestimate crop water use.

The enclosed simple procedures provide a method to adjust the default FAO-56 crop coefficient values for any locale in the USA and her possessions.

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Comparison of irrigation scheduling methods in the humid Mid-South

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ABSTRACT

The appropriate scheduling of irrigations can result in more efficient use of water and energy resources, improved yields, and reductions in runoff and off-site pollution. Fields planted to cotton in the lower Mississippi Delta region of the humid Mid-South were irrigated based on four scheduling methods: 1) the original Arkansas Irrigation Scheduler, 2) an updated (2008) Arkansas Irrigation Scheduler, 3) a spreadsheet with an FAO-56 ET-water-balance model, and 4) a soil-moisture sensor-based method. The different methods did provide guidance on when to irrigate, but assumptions built into the models led to differences in schedules under certain conditions. Violating the assumptions led to under-irrigation in some cases, and reductions in yield. Yields were affected by tillage practices, with yields slightly higher under minimum-tillage conditions. Soil type also affected the potential usefulness of any scheduling method, with irrigation treatments in a clay soil resulting in yields lower than those from non-irrigated treatments.

INTRODUCTION

The appropriate scheduling of irrigations can result in more efficient use of water and energy resources, improved yields, and reductions in runoff and off-site pollution. Irrigation scheduling is common in arid and semi-arid regions, where irrigation is required due to inadequate rainfall. In the humid Mid-South region of the US, where rainfall is more frequent, the use of irrigation is increasing. Irrigation is used as a supplemental source of water for those times when rainfall is insufficient to meet crop-water needs.

A variety of scheduling methods exist and range from simple, soil-feel and visual methods to more scientific methods. Computer-based models often use weather data and a water-balance approach to keep track of water incoming (rainfall, irrigation) and outgoing (evapotranspiration) to determine when soil-water resources become depleted. Sensor-based systems monitor conditions in the field, and give an indication of the soil-water status directly.

Tillage practices and soil conditions can interact with crop growth and irrigation-water requirements. Field conditions affect the timely application of irrigation water and can impact crop yield and water-use efficiency.

Objectives

The objectives of the study were to test the impact of four irrigation scheduling methods under differing soil and tillage conditions on final harvest yield. The four scheduling methods included the original Arkansas Irrigation Scheduler, an updated (2008) Arkansas Irrigation Scheduler, an FAO-56 ET-water balance method, and a soil-moisture sensor-based method. Tillage treatments included conventional and minimum-tillage preparations.

EXPERIMENTAL SETUP

The study was conducted at the Jamie Whitten Delta States Research Center, Stoneville, Mississippi USA, during the 2008 growing season. The research center is located at approximately 33.4°North latitude and 90.9°West longitude, at an elevation of 125 feet above sea level.

Three fields, designated AP2-1, AP2-2, and MF4, were used in the study. Each field was prepared for raised-bed, furrow-irrigated production on a 38-inch row spacing. Soil types in fields AP2-1 and AP2-2 varied across the fields, and consisted of Tunica clay, Dundee silty clay loam, and Dundee very fine sandy loam. The soil in field MF4 was more uniform and consisted mainly of Tunica clay. The fields were subdivided into small plots, each 8 rows wide. Fields AP2-1 and AP2-2 measured 780 ft long and had 15 plots each. Field MF4 measured 450 ft long and contained 20 plots.

Fields were prepared under two tillage systems; conventional tillage in fields AP2-1 and MF4, and conservation, or minimum tillage in field AP2-2. Conventional tillage consisted of those practices in common use by producers in the Mid-South region. Following harvest in the fall, stalks were shredded, fields were lightly disked, and the rows were bedded up and left to settle during the winter. The following spring, the rows were rehipped and then knocked down to form a stable seed bed, and the field was planted.

Minimum-tillage is a practice which is becoming increasingly common as producers look to reduce input labor and costs. In the fall, stalks were shredded, and a roller with busters was pulled across the field to form shallow furrows for drainage and irrigation. In the spring, the fields were planted, and if needed, the roller/busters were used again clean out the furrows to help facilitate irrigations.

The fields were surface irrigated by pumping groundwater from a nearby well through flexible polypipe containing adjustable plastic gates. Each field was supplied through a separate length of polypipe, and was instrumented with a propeller-type flow meter. Adjustable plastic gates allowed the plots in each treatment to be irrigated as needed: gates were open when a plot was to be irrigated and closed when no irrigation was required.

Scheduling methods

Four scheduling treatments, and a non-irrigated treatment, were replicated in each field. Fields AP2-1 and AP2-2 had three replicate plots per treatment, and field MF4 had four plots per treatment. The four irrigation scheduling methods consisted of 1) the original Arkansas Irrigation Scheduler, 2) an updated (2008) Arkansas Irrigation Scheduler, 3) an FAO-56 ET-water balance method, and 4) a soil-moisture sensor-based method.

The Arkansas Irrigation Scheduler is a computer model developed by the University of Arkansas Cooperative Extension Service (Ferguson et al., 2000). The program uses a water-balance approach to calculate a daily soil-water deficit. The user enters general field, soil, crop, and irrigation-system information into the program at the beginning of the season to configure the model. Daily air temperature, precipitation, and irrigation data are then entered throughout the growing season. The program calculates a daily reference ET using an empirical temperature-based method, and a built-in crop coefficient function is applied to estimate crop ET. The daily soil-water deficit is determined by adding the crop ET to the previous day's deficit and subtracting any rainfall that occurred. When the deficit reaches a critical, allowable deficit, established by the user, an irrigation is needed.

In 2008, an updated version of the Arkansas Irrigation Scheduler was released (Vories et al., 2005). The main enhancement over the original version was the ability of the user to enter daily reference ET values rather than temperature values. This allowed the user to bypass the empirical temperature-ET relationship of the original program and enter ET values determined locally, from an evaporation pan or using more complete weather data and a more sophisticated ET model. Other features (crop coefficient functions, water-balance routine, irrigation criteria, etc.) from the original program were retained. The ability to enter reference ET values is an improvement, however, the crop coefficient functions need further attention. Crop coefficients are unique to the reference-ET method used in their development and may not be appropriate if applied to a different reference-ET method.

A third water-balance model was developed which used a standard computer spreadsheet to record daily weather data, calculate daily reference- and crop-ET values, and determine daily soil-water deficits. The FAO-56 Penman-Monteith reference-ET model (Allen et al., 1998) and a locally-developed crop coefficient function (Fisher, 2004 and additional unpublished data) were used to estimate crop ET. Precipitation and irrigation amounts measured at each field completed the water-balance data. Daily cumulative soil-water deficits were calculated, with critical, allowable deficit values estimated from the NRCS Soil Survey for the area (SCS, 1961).

In the soil-moisture sensor treatments, sensors were installed in each plot and connected to dataloggers. Granular matrix sensors (Watermark SS-200, Irrometer Co., Riverside, CA) were installed at three depths, 6-, 12-, and 24-in below the soil surface, at two locations in each plot. Sensor measurements were collected and stored automatically at two-hour intervals using battery-powered dataloggers (Fisher, 2007). Sensor data were monitored to determine when soil moisture status reached a critical value, at which time an irrigation was needed.

Scheduling procedures

Irrigations of the plots under each scheduling treatment in the three fields were scheduled independently of each other. Daily weather and precipitation data were input to each of the computer models, and daily soil-water deficits were calculated. Data from the soil-moisture sensors were downloaded periodically and input to a spreadsheet in order to monitor daily soil-water status. For each treatment, when the critical allowable-deficit level was reached, an irrigation was scheduled.

Critical allowable-deficit levels were determined for each scheduling method. Both Arkansas Irrigation

Schedulers offered guidance on selecting the allowable limit based on soil, crop, and irrigation system information. The level selected for this study was 2.5 in of water. For the water-balance spreadsheet model, information provided in the SCS soil survey suggested an allowable deficit of 2.5 in also. For the soil-moisture sensor plots, a level of –60 cbar was chosen.

Upon reaching the allowable limit, an irrigation was scheduled. The adjustable plastic gates in each plot to be irrigated were opened, and water was applied to replenish the deficit. The amount of water applied was measured with flowmeters and converted to an equivalent depth for each plot. The water balances for each computer model were then updated to reflect the irrigation event.

At the end of the season, the plots were harvested individually and total plot yields were measured. The center four rows of each plot were harvested with a four-row mechanical spindle harvester. The cotton was then transferred to a boll buggy equipped with electronic loadcells, and the total weight of the cotton was measured and recorded. Yield from the two rows on either side of the center four rows was not measured: conditions in adjoining plots may have affected these edge rows, resulting in crop growth and yield inconsistent with that due to the plot treatment.

RESULTS AND DISCUSSION

Weather data from the Mississippi State University weather station at Stoneville were collected for input to the irrigation scheduling models. Weather data were input to the RefET Reference Evapotranspiration Calculator software (Allen, 2002) to estimate daily reference ET using the FAO-56 method. These reference ET values were input to the 2008 Arkansas Irrigation Scheduler and the spreadsheet water-balance model. Maximum daily air temperature was input to the original Arkansas Irrigation Scheduler.

Rainfall

Precipitation amounts were measured with raingages located at each of the fields. Rainfall is highly variable spatially in the Mid-South, and can vary greatly over a short distance. To illustrate this, rainfall amounts measured during May 2008 in field MF4 and at the weather station, which are approximately 3 miles apart, are shown in Table 1. Rainfall measured at the weather station was over 2 inches greater than that measured in field MF4.

The difference in rainfall amounts could have a significant affect on water-balance calculations and irrigation schedules. If the weather-station data had been used, the irrigation schedule may have indicated that the soil-water deficit was less than the allowable amount, while in fact, the soil may have been much drier. If rainfall is highly variable, locally measured data must be used to give an accurate account of conditions in the field.

Irrigation schedulers

The four scheduling methods were run throughout the growing season. The weather-based models were updated daily, and the soil-moisture sensor data were collected weekly and input to a spreadsheet for analysis. When the soil-water deficit reached the allowable limit for each method, an irrigation was scheduled. Each irrigation was planned to occur the following day, but on several occasions other field operations delayed the irrigation for up to several days.

Resulting irrigation schedules for each of the four scheduling methods for field MF4 are shown in Figure 1. Each schedule shows the daily soil-water deficit, allowable deficit, rainfall amounts, and irrigation events that occurred during the growing season. Three of the methods resulted in three irrigations being scheduled in the middle of the season. One method, the updated Arkansas Irrigation Scheduler, called for only two irrigations. In the latter part of the season, rainfall was sufficient so that no further irrigations were required.

Daily reference ET values calculated by the FAO-56-based method were lower than those from the temperature-based routine in the original Arkansas model. The same crop coefficient functions were used in both Arkansas models, and the lower ET values resulted in the updated Arkansas model (Figure 1b) calling for one less irrigation than the original model (Figure 1a). The spreadsheet water-balance model (Figure 1c), which also used the FAO-56 reference ET values, used a different crop coefficient, and resulted in

Table 1. Precipitation measured during May 2008 with an in-field raingage and at the weather station.

Day	**Raingage readings**	
	field MF4 in	**weather station in**
2	0.43	0.63
7	0.16	0.24
8	0.04	0.12
13	0.35	0.43
14	0.91	1.85
15	0.39	0.51
22	0.28	0.67
24	0.31	0.31
27	1.89	2.12
total	**4.76**	**6.88**

a seasonal schedule similar to the temperature-based model (Figure 1a).

The soil-moisture sensors measured actual conditions in the field and did not rely on any calculations or additional data collection. The resulting schedule (Figure 1d) agreed well with the other models.

One of the main assumptions in the Arkansas Irrigation Scheduler models deals with what happens after an irrigation. The Arkansas models assume that when an irrigation event occurs, the irrigation is sufficient to replenish the soil-water deficit, and the soil-water deficit is reset to zero. The amount of irrigation water applied is not entered into the scheduling program, but rather only an indication that an irrigation occurred. The graphs in Figures 1a and 1b reflect this by showing a vertical bar with length 1 when an irrigation occurred. In the other schedulers (Figures 1c and 1d), the actual amount of irrigation water applied is shown.

Irrigation schedules for fields AP2-1 and AP2-2 were similar but highlighted the Arkansas schedulers' idea that every irrigation was sufficient to reset the soil-water deficit to zero. Infiltration problems in these fields made it difficult to apply adequate amounts of

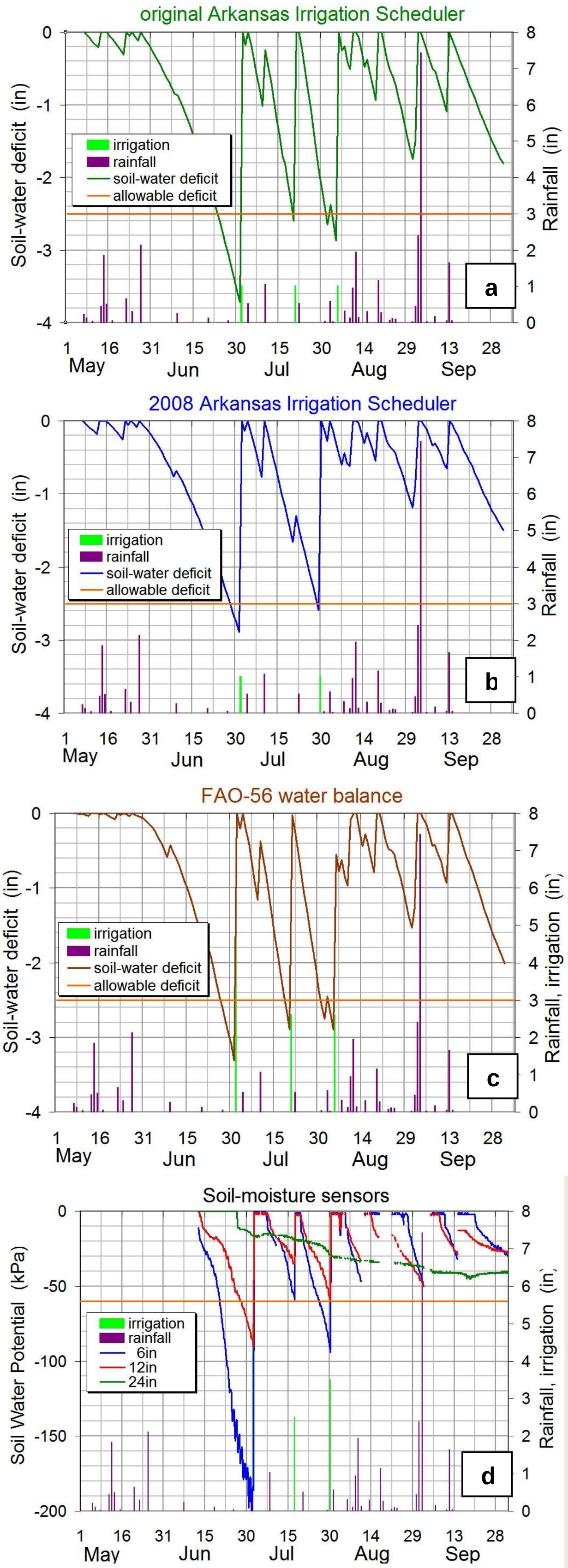

Figure 1. Irrigation schedules from each of the four scheduling methods for field MF4.

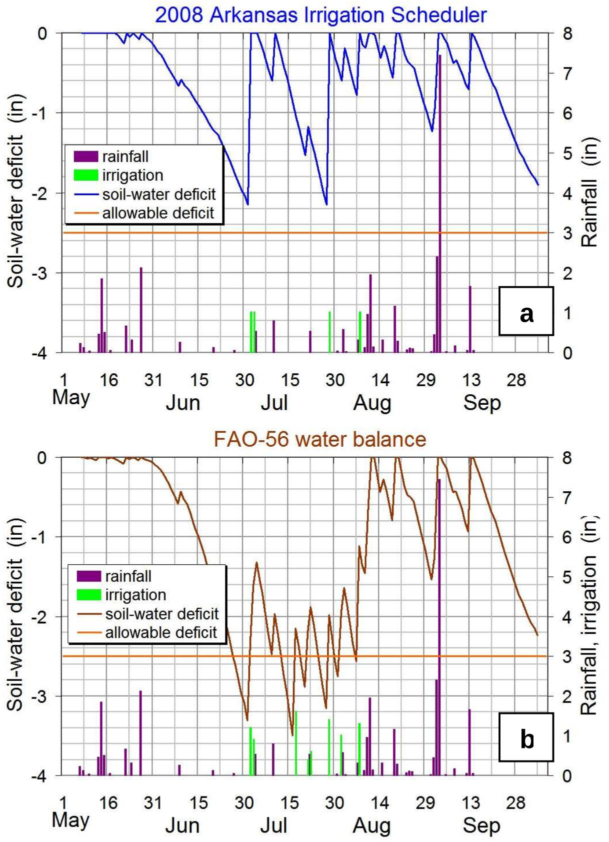

Figure 2. Irrigation schedules for two scheduling methods for field AP2-1.

water during an irrigation. Based on flowmeter readings, equivalent depths of irrigation ranged from 0.4 to 1.4 in before irrigations were ceased in order to prevent excessive runoff. In some cases, water was able to be applied for two consecutive days, but total water applied was usually less than 1.5 in.

In Figure 2, schedules are shown for two methods for field AP2-1. In Figure 2a, the Arkansas scheduler shows three irrigation events: two irrigations were called for based on the soil-water deficit values approaching the allowable limit, but a third irrigation was made to try to apply additional water to make up for the inadequate second irrigation. If flowmeter readings had not been available, each irrigation would have been assumed to be adequate and only two irrigations would have been made.

The FAO-56 water-balance method in Figure 2b shows six irrigations. This method used the actual amount of water applied form each irrigation to update the soil-water deficit rather than resetting the deficit to zero. This method shows that the irrigations were not sufficient, resulting in many more irrigation events being needed. This method also resulted in more water being applied, further indicating that the amount of water applied using the Arkansas scheduler was insufficient.

Table 2. Amount of irrigation water, total water, and yield for each treatment.

Treatment	**Irrig water applied in**	**Yield ba/ac**
AP2-1 (conventional tillage)		
Original Arkansas Scheduler	5.4	1.46
2008 Arkansas Scheduler	4.8	1.43
FAO-56 water balance	8.4	1.67
Soil-moisture sensors	7.0	1.56
Non-irrigated		0.95
AP2-2 (minimum tillage)		
Original Arkansas Scheduler	5.7	1.56
2008 Arkansas Scheduler	4.9	1.49
FAO-56 water balance	8.4	1.72
Soil-moisture sensors	6.9	1.73
Non-irrigated		1.23
MF4 (conventional tillage)		
original Arkansas Scheduler	10.1	1.69
2008 Arkansas Scheduler	8.5	1.62
FAO-56 water balance	10.1	1.77
Soil-moisture sensors	11.0	1.63
Non-irrigated		1.82

Yield

Yields from the replicate plots in each treatment were measured, averaged, and then converted to yield on an areal basis. Cotton yield from each plot in each of the fields is shown in Figure 3. Average yield for each scheduling method is listed in Table 2. Also listed in Table 2 are the amounts of irrigation water applied for each scheduling treatment.

Yield differences were observed among the four irrigation scheduling treatments and the non-irrigated treatment in each field. An analysis-of-variance (ANOVA) procedure was run on the plot data shown in Figure 3 for each field (results not shown), which

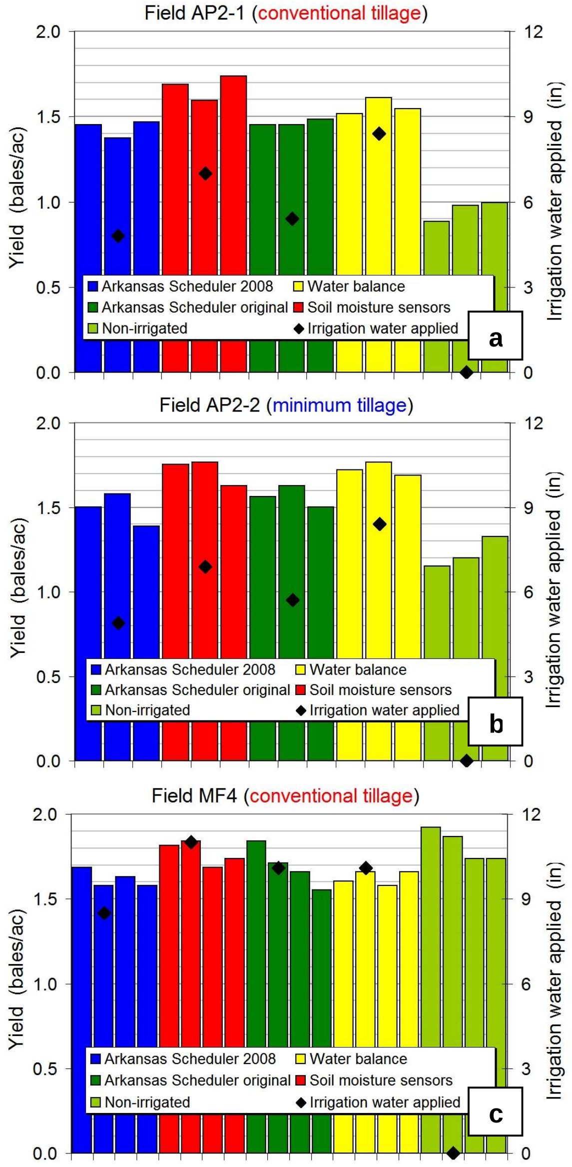

Figure 3. Cotton yield from each plot in each field.

indicated that there were significant differences in yield among the scheduling treatments. The differences in yield were not consistent among the different fields, however, suggesting that no particular scheduling method outperformed the others in terms of yield.
In fields AP2-1 and AP2-2, yields correlated with the amount of irrigation water applied, with higher yields resulting from more water applied. The non-irrigated treatments yielded the lowest, and yields increased as applied water increased. The FAO-56 water-balance and soil-moisture sensor methods returned the highest yields since those treatments also received the most irrigation water. In these fields, where infiltration problems resulted in irrigations which did not completely replenish the soil-water deficits, these two scheduling methods maintained a more accurate account of field conditions than did the Arkansas schedulers.

In field MF4, however, the non-irrigated treatment returned the highest yields. In this case, soil type may have been the determining factor. The clayey soil had sufficient soil-water resources throughout the season, and the irrigations added excess water which affected crop growth and depressed yield. Under the weather conditions experienced this season, and on this type of soil, irrigation was unnecessary and no scheduling method would have improved yields.

Fields AP2-1 and AP2-2 were also part of another study examining the effects of tillage practice on cotton yield. The fields were adjacent to each other and had similar soils, with field AP2-1 under conventional tillage and AP2-2 under minimum tillage conditions. Under each of the irrigation scheduling treatments, yields under minimum-tillage conditions were higher than those under conventional tillage. Yield increases ranged from 3 to 10% in the irrigated treatments, and were 29% higher in the non-irrigated plots.

CONCLUSIONS

Irrigation scheduling is an important tool for meeting the irrigation-water requirements of a crop. Three computer-based scheduling models and a soil-sensor-based method were used to schedule irrigations in several fields throughout the growing season. The four methods proved fairly simple and easy to use, and provided guidance on determining when to irrigate.

While the computer-based models used weather data from a weather station located several miles away from the fields being irrigated, it was important that rainfall be measured at the field. Rainfall is an important component in the water-balance models, and needs to accurately reflect field conditions.

One of the main assumptions of the Arkansas Irrigation Schedulers is that each irrigation event is sufficient to fully replenish the soil-water deficit, resetting the deficit to zero. In cases of insufficient irrigation water being applied, the Arkansas schedulers would still reset the deficit to zero but the actual soil-water deficit would be greater than that. This could result in the following irrigation being indicated later than needed, and the actual soil-water deficit becoming much greater than the allowable limit. This could be avoided by measuring the amount of water applied with a flowmeter to ensure that the irrigation was adequate.

Another alternative would be to use a water-balance method which allowed input of the measured depth of water applied. This would allow a more complete accounting of the water-balance components, and help maintain an accurate estimate of the soil-water deficit. To avoid the need to input any weather data or rely on the construction and assumptions of a computer model, soil-moisture sensors provide measurements of the actual soil-water conditions in the field.

Soil-type interacted with irrigation scheduling and yield in that some soils do not respond to irrigation. Irrigation under certain soils conditions may not be appropriate at all, and yield depression could result.

DISCLAIMER

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A Simple Irrigation Scheduling Approach for Pecan Irrigation in the Lower Rio Grande Valley

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ABSTRACT

Pecan is a major crop in the lower Rio Grande Valley (LRGV), New Mexico. Currently, about 12,000 ha of pecan orchards at various stages of growth are consuming about 45 percent of irrigation water in the area. Pecan evapotranspiration (ET) varies with age, canopy cover, soil type, crop density and method of water management. The intense competition for the limited water supply in the area has created a serious need for better water management through improved irrigation scheduling. Pecan annual ET varies from as low as 500 mm to as high as 1400 mm. The diversity of the crop coefficient and ET makes the task of irrigation scheduling in this particular crop very complicated.

Using remote sensing technology and field ET measurement, a simple relationship was developed to relate crop coefficient and ET to canopy cover. This relationship is then used in combination with climate data to calculate daily and weekly water requirement for each orchard.

The methodology provides a simple tool that a typical farmer can use to schedule irrigation for pecan orchards.

INTRODUCTION

Pecan is a major crop in Lower Rio Grande Valley (LRGV) currently comprising about 46% of the irrigated acreage. Pecan production in LRGV has steadily increased in the past 40 years reaching to about 30,000 acres in 2008. Pecan is a major cash crop in NM with average annual income of 40 million dollars. Pecan is also a major water user. A mature pecan orchard can consume about 4.3 ft of water per year. The high water use and increasing acreage of pecan combined with periodic and severe drought in NM has created an urgent need for better understanding of pecan consumptive use and better management of water in the area.

There are various methods to estimate crop water use, but because of the diversity of pecan age, spacing, density and management practices, real time estimation of crop consumptive use is complex and beyond the reach of individual farmers. This paper describes a simple approach to estimate average daily and monthly crop ET.

METHODOLOGY

Using remote sensing technology, a simple relationship was developed to relate crop coefficient and ET to canopy cover. This relationship is then used in combination with climate data to calculate daily and weekly water requirement for each orchard.

The methodology provides a simple tool that a typical farmer can use to schedule irrigation of Pecan orchards. The remote sensing uses Landsat images combined with surface energy balance technique to calculate daily water use on the ground. The regional ET estimation model (REEM, Samani et al, 2007, 2009) calculates ET as a residual of surface energy balance. The methodology is similar to one presented by Bastiaanssen et al (1988) with some modification as described by Samani et al (2008) where the latent heat flux (LE) was determined as a residual of the surface energy equation:

$$ET = R_n - G - H \qquad (1)$$

Where, ET is the latent heat flux (evapotranspiration), R_n is the net radiation flux at the surface, G is the soil heat flux, and H is the sensible heat flux to the air.

After calculating daily ET, monthly and annual ET values, pecan fractional cover in various orchards was estimated using a series of infrared-DOQQs images which were taken from aerial flights. Fractional cover was estimated using supervised classification of the masked and subset color infrared DOQQs. Supervised classification is a common method used to group pixels similar in reflectance based on training classes. The training phase consists of assigning sets of pixels to a particular class based on previous knowledge of the image or verification on the ground (Bastiaanssen, 1998).

Figure 1 shows a relationship between annual ET and fractional cover (f_c) for 279 pecan orchards. The information in figure 1 was used to develop a relationship between relative crop coefficient and fractional cover (figure 2). The relative crop coefficient was defined as the ratio of average annual crop coefficient of an orchard (k_c) to that of a fully mature reference orchard with canopy cover of about 80 percent in which daily ET was measured using an eddy covariance flux tower.(Reveles, 2005).

Using figure 2, and the K_c of the reference orchard, the daily, weekly or monthly kc values for individual orchards can be estimated as:

$$K_c = \left(\frac{K_c}{K_{c-ref}}\right) K_{c-ref} \qquad (2)$$

In which $K_{c\text{-}ref}$ represent the crop coefficient of the reference orchard. The monthly k_c values for the reference orchard are shown in Table 1.

Table 1, Measured monthly K_c for the reference Pecan orchard ($K_{c\text{-}ref}$) using flux tower

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kc	0.38	0.36	0.39	0.59	0.87	1.02	1.04	1.24	1.26	0.84	0.39	0.38

Once the K_c values are estimated, the daily crop ET can be estimated using the relationship between crop ET and reference evapotranspiration estimated from climate data as:

$$ET = K_c \, . \, ET_0 \qquad (3)$$

in which ET is daily, week or monthly ET and ET_0 is reference evapotranspiration calculated from Hargreaves-Samani equation (1985) or Penman-Monteith (ASCE-EWRI 2005).

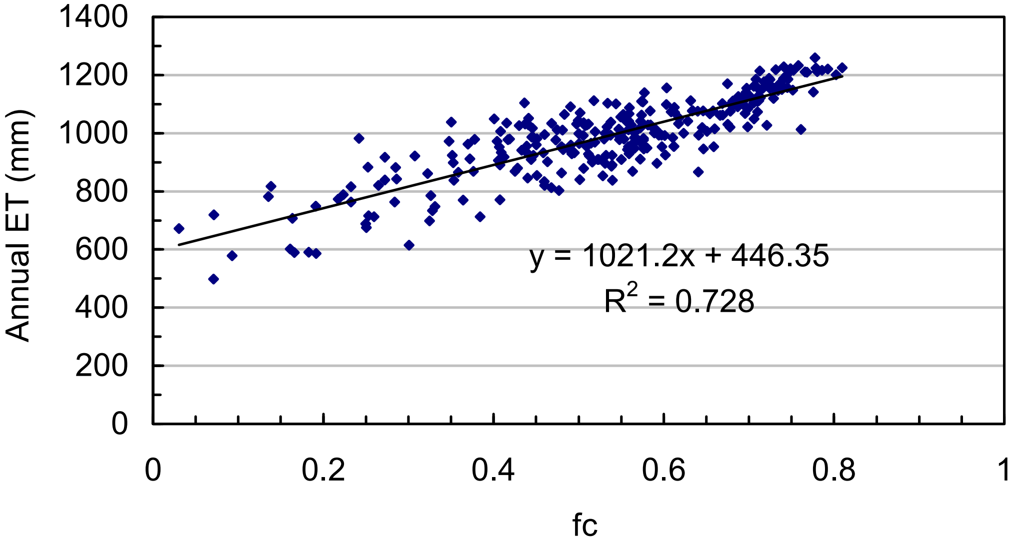


Fig. 1. Relationship between Annual Pecan ET and fractional cover (f_c) for various orchards.

Figure 3, 4 and 5 compare the estimated monthly pecan K_c with remotely sensed K_c values of the same orchards for three fractional cover of 40%, 60% and 73% respectively.

FIELD COMPARISON

The methodology described above was used to estimate monthly ET for a young pecan orchard with average fractional cover of 52%. An eddy covariance flux tower installed in the same orchard was used to measure daily ET. Figure 6 compares measured and estimated monthly ET for the orchard. The maximum monthly ET difference is about 9.5%.

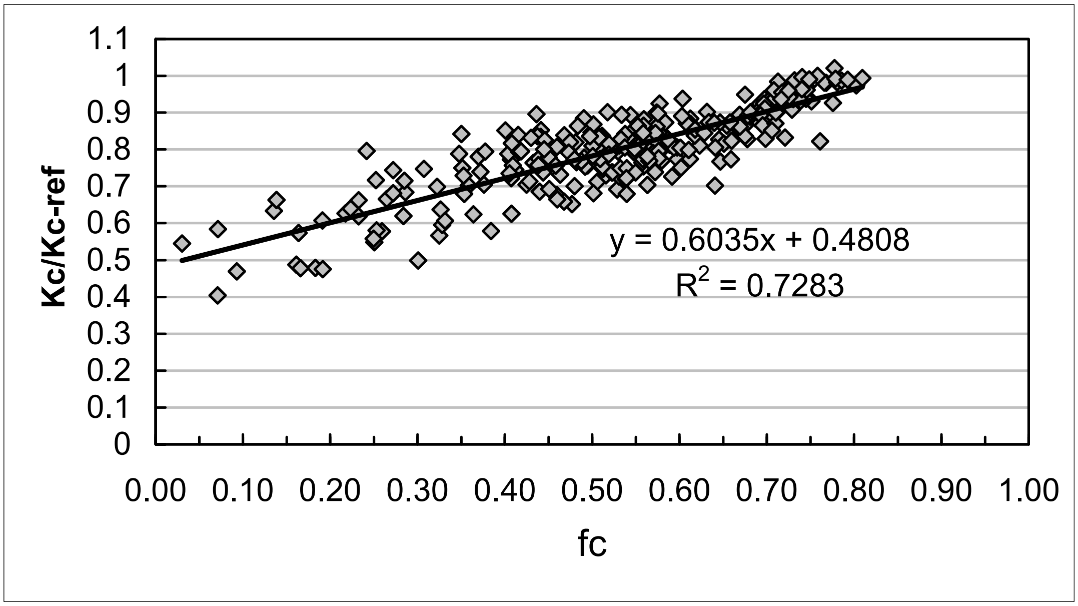


Fig. 2. Relationship between relative crop coefficient and fractional cover (fc).

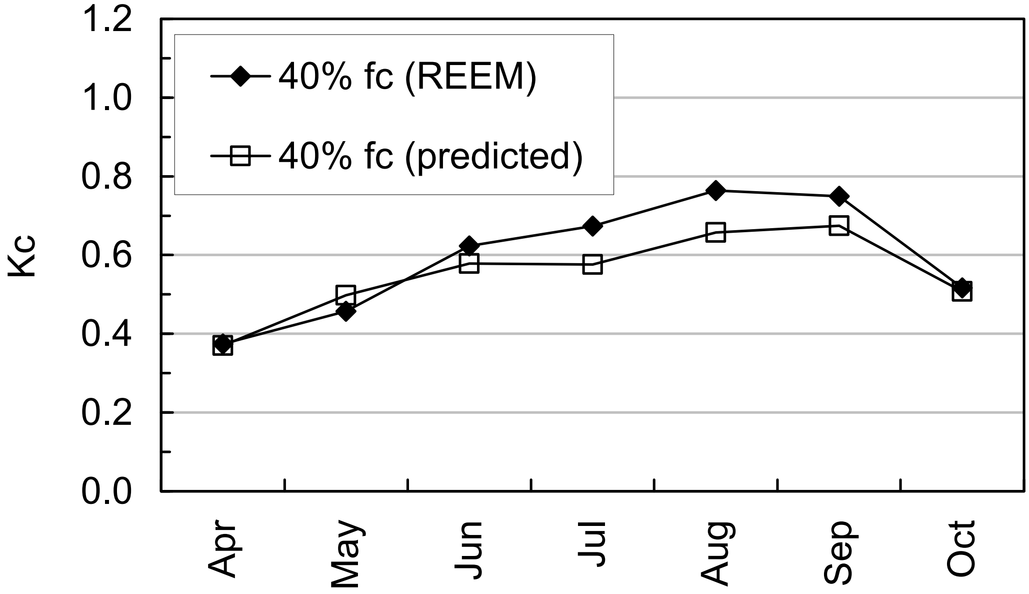


Fig. 3. Comparison of estimated K_c with remotely sensed K_c for 40% fractional cover

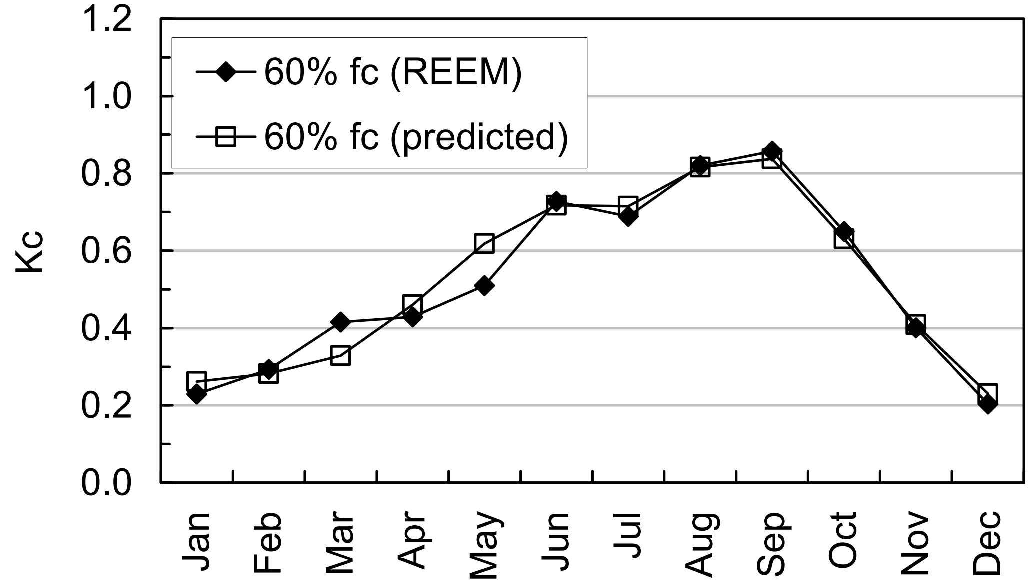


Fig. 4. Comparison of estimated K_c with remotely sensed K_c for 60% fractional cover

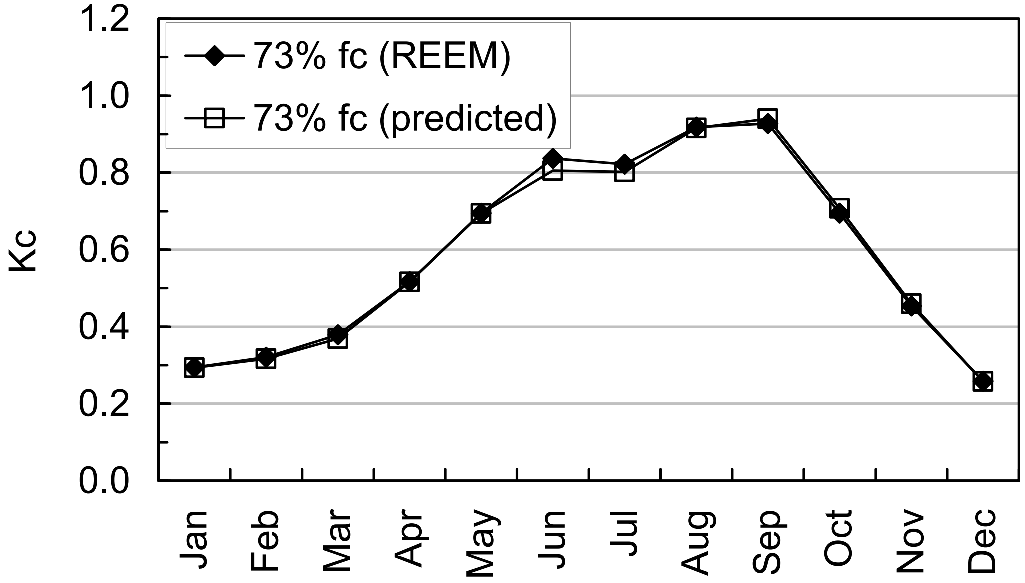
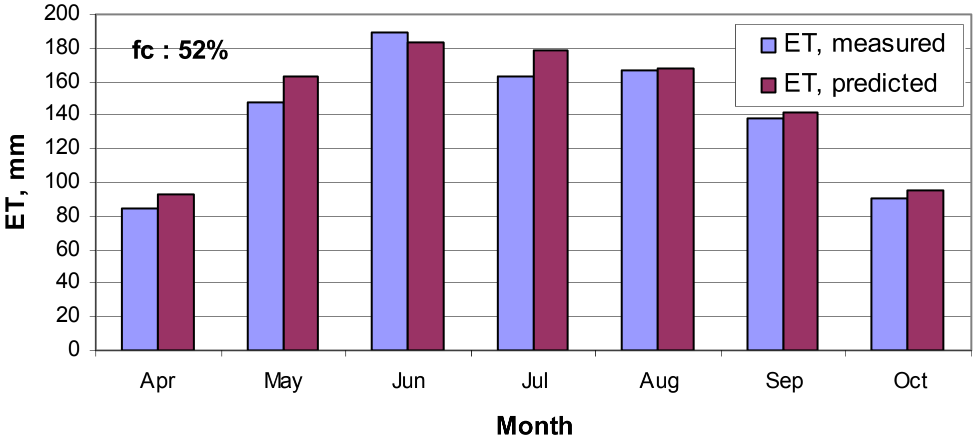


Fig. 5. Comparison of estimated K_c with remotely sensed K_c for 730% fractional cover



CONCLUSION

A simple procedure is presented where crop fractional cover/canopy cover can be used to estimate average daily ET of pecan. The comparison between measured ET and predicted ET showed that average monthly ET can be estimated with high accuracy. The procedure provides a simple approach to calculate pecan ET. The information can then be combined with soil physical properties to develop irrigation schedules for each orchard.

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AgriMet: Reclamation's Pacific Northwest Evapotranspiration Network

Peter L. Palmer[1]

ABSTRACT

In 1983, the Bureau of Reclamation (Reclamation) and Bonneville Power Administration (BPA) partnered to create a network of automated agricultural weather stations called "AgriMet" in the Pacific Northwest. These stations collect and telemeter the meteorological parameters required to model crop evapotranspiration (ET). Since the installation of three stations in 1983, the network has grown to over 90 automated weather stations in the Northwest. The information is used by irrigation districts, farmers, resource conservation agencies, and agricultural consultants for irrigation scheduling and related purposes. Use of AgriMet information in irrigation scheduling results in water and energy savings, reduced soil erosion, and protection of surface and ground water supplies. Near real time hourly weather data from AgriMet is also used for a variety of applications, including peak power load forecasting, agricultural frost protection, and short term weather forecast verification.

INTRODUCTION

Modeling ET with weather data has evolved over the years with refinements in modeling procedures and data collection methods. Current technologies typically involve automated agricultural weather stations and data transfer by satellite, phone, radio, or wireless networking. Powerful computers now make fast work of the typically complex mathematical ET models, and the Internet makes the information almost instantly available to the users of the information.

In 1983, Reclamation and BPA began an initiative to promote efficient irrigation water use in the Columbia River basin. This partnership resulted in the installation of a network of automated agricultural weather stations called "AgriMet" (for Agricultural Meteorology) in the Pacific Northwest. These stations collect and telemeter the meteorological parameters required to model crop consumptive water use. Since the initial installation of 3 stations in 1983, the network has grown to over 60 stations in Reclamation's Pacific Northwest Region, 22 stations in the Great Plains Region in Montana (east of the Continental Divide), and 7 stations in the Mid Pacific Region. Reclamation has established partnerships with more than 25 entities, including other federal and state agencies, soil and water conservation districts, universities, public utilities, and private enterprise to help fund the operation of the AgriMet network.

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AGRIMET DATA COLLECTION AND TRANSMISSION

AgriMet stations are located in agricultural areas throughout Idaho, Montana, Oregon, and Washington, with a few additional stations located in northern California, western Wyoming, and Nevada (Fig. 1). The weather stations are typically located on the edge of irrigated fields so that the observed weather data approximates the meteorological conditions affecting the cultivated crops in the area (Fig. 2). Each AgriMet station is configured with a standard set of sensors, including air temperature, precipitation, solar radiation, wind speed and direction, and relative humidity. These standard sensors measure the meteorological parameters required for modeling crop ET. Some sites have special sensors, including soil temperature, diffuse pyranometers for special solar radiation studies, crop canopy temperature, leaf wetness, and evaporation pan sensors.

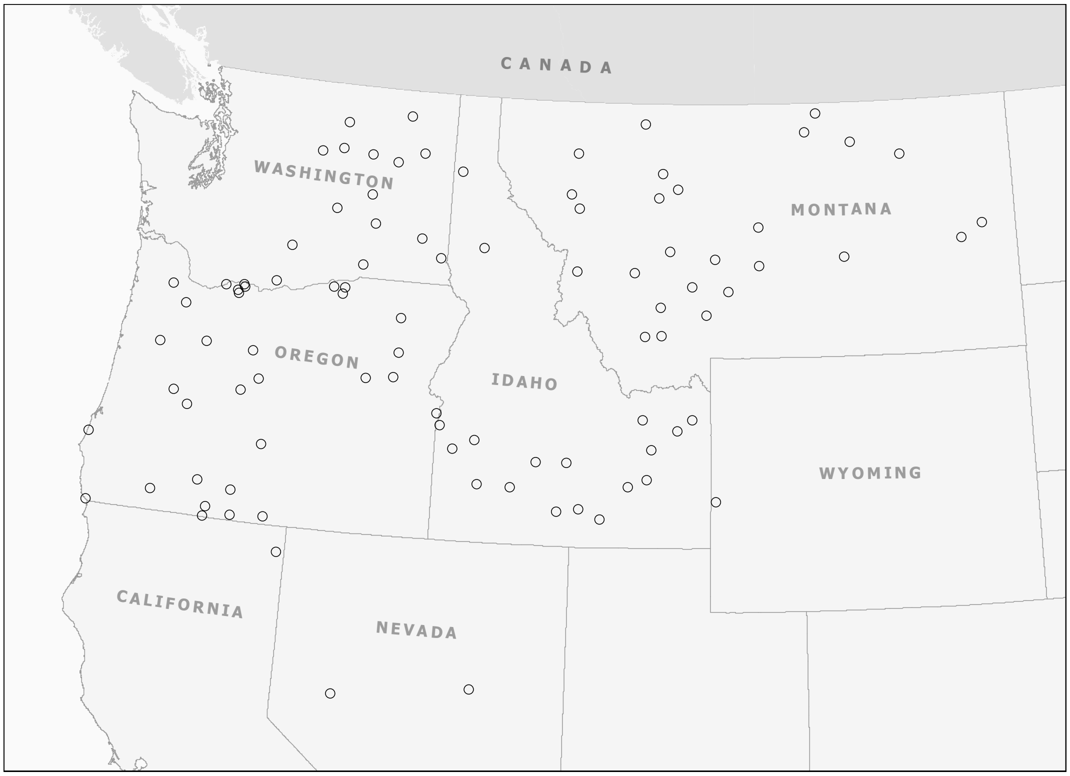

Figure 1. AgriMet Weather Station Locations in the Northwest

All the weather station components, including sensors, solar panel, antenna, data logger and transmitter are mounted on a sturdy aluminum tripod. Sensors are mounted at standard sensor heights for agricultural weather data collection requirements (typically 2 meters). Power for each weather station is provided by a heavy duty lead acid storage battery that is recharged daily by a solar panel.

The data logger at the site measures each of the weather sensors once every second. These readings are used to derive the final data parameters for subsequent transmission, such as 15 minute air temperature observations, total hourly precipitation, etc. These parameters are transmitted once an hour via the Geostationary Operational Environmental Satellite (GOES) to a receive site at Reclamation's Pacific Northwest Regional Office in Boise, Idaho. The receive site also down-links data for other Reclamation programs, as well as for other cooperating federal agencies.

Reliability of the data transmissions over the GOES satellite is excellent; in 2009 the AgriMet network received 99.95 percent of expected transmissions; only 200 hourly transmissions were missed out of nearly a half million expected transmissions.

Figure 2: Typical AgriMet Station

DATA QUALITY ASSURANCE PROCEDURES

Quality assurance for the AgriMet program consists of five interrelated components: laboratory calibration of weather sensors, an annual maintenance and calibration visit to each weather station, automated data quality control procedures, manual data quality control procedures, and an annual review of weather and associated evapotranspiration parameters.

Good data quality begins with accurate, reliable sensors in the field. In order to minimize station downtime and to respond rapidly to sensor failures, vandalism, or other problems, the AgriMet network maintains approximately a ten percent overstock of spare sensors and components. These sensors and components are maintained in a calibrated state for use anytime during the year, or for sensor replacement during annual site maintenance and calibration visits.

All AgriMet sites receive an annual maintenance and inspection visit in the spring that includes calibration and maintenance of all sensors. Data logger and transmitter parameters are checked for conformance to specifications. System battery voltage, solar panel output, and voltage regulator output are checked; these items are replaced or adjusted as needed. All sensors are compared against laboratory calibrated standards and are adjusted or replaced as needed. This special attention given to the sites during these annual calibration and maintenance visits provides high quality meteorological data not only for crop water use modeling, but also for a variety of research and other weather related applications.

Immediately upon receipt from the GOES satellite, the weather data is subjected to several automated quality control procedures. These tests include a check of satellite transmission data quality parameters, upper and lower value limit tests, and rate of change tests. If the incoming data fails any of these checks, it is marked with a flag indicating the nature of the failure before being added to the database. These flagged values are not used in subsequent calculations, such as computation of average daily temperatures or daily ET rates.

In addition to the automated checks, a manual quality control review is performed on the data each working day. These procedures include review of satellite transmission quality parameters that may point to data quality problems not detected by the automated procedures. Other checks include graphical review of sensor data by groups of sites that have similar climatic characteristics. Apparent anomalies are examined for possible data quality problems, and bad data are removed or estimated. Summary parameters, such as mean daily temperature, and ET values are then recalculated using the revised weather data. These changes are reposted to the AgriMet website.

At the conclusion of each year, an AgriMet technician reviews annual graphs of weather data and crop consumptive water use in both climatologically and geographically similar groups, as well as individually. Reviewing these annual graphs allows for quick identification of data errors that may have been previously overlooked.

AgriMet's multi-faceted quality assurance procedures result in a very complete, accurate, and timely database of meteorological and crop water use information, all easily accessible on the Internet.

EVAPOTRANSPIRATION MODELING

AgriMet uses the 1982 Kimberly-Penman equation for computing reference ET, adapted by Dr. James L. Wright of the USDA Agricultural Research Service through his research performed in Kimberly, Idaho (Jensen et al. 1990). This procedure requires several meteorological inputs for modeling ET, including maximum and minimum daily air temperatures, relative humidity, daily solar radiation, and daily wind run. All of these parameters are collected by the AgriMet network.

The 1982 Kimberly-Penman model uses alfalfa as the reference crop, with reference conditions defined as a well-watered alfalfa crop with 30 to 50 cm of top growth. The equation, as implemented in the AgriMet program, is represented as:

$$\lambda ET_r = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} 6.43\, W_f (e_s - e_a) \tag{1}$$

Where:

λETr is reference evapotranspiration
Δ is the slope of the saturation vapor pressure-temperature curve
γ is the psychrometric constant
R_n is the net radiation
G is the soil heat flux
6.43 is the constant of proportionality in MJ/m^2/d/kPa.
W_f is the dimensionless wind function
$(e_s - e_a)$ is the mean daily vapor pressure deficit in kPa.

Because of the variability of ET rates from crop to crop and the complexity of modeling ET, the accepted standard for deriving crop specific ET (ETc) is to model ET for a reference crop, such as alfalfa (ETr), and then apply this reference ETr value to specific crops through the use of crop coefficients (Kc). These crop coefficients are unique to the reference crop and the individual specific crop, and they vary through time with the growth stage of the plant. Crop coefficients typically are expressed as a percentage of water use compared to the reference crop (Fig. 3). In equation form, the crop coefficient methodology is represented as:

$$ETc = ETr * Kc \tag{2}$$

Where:

ETc = Crop specific evapotranspiration
ETr = Reference evapotranspiration (alfalfa reference)
Kc = Crop coefficient for a specific crop.

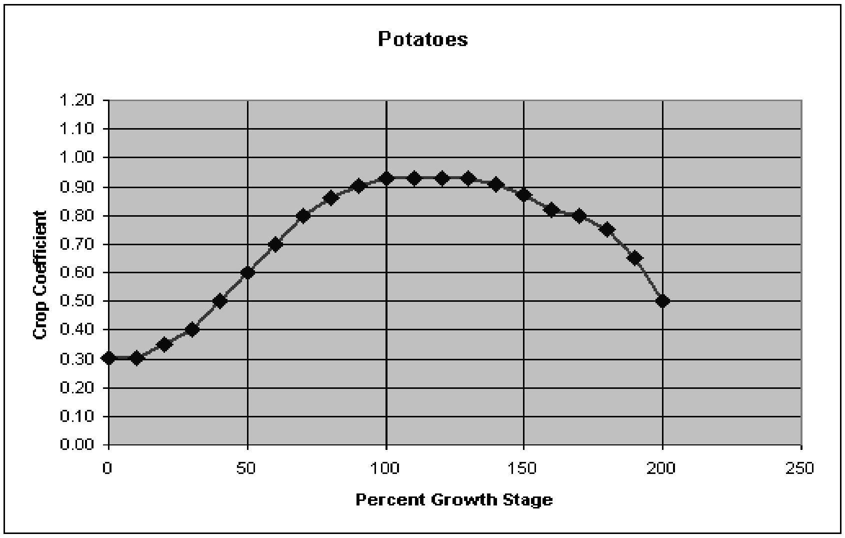

Figure 3. Example of Crop Coefficient Curve used by AgriMet

Crop coefficients have been developed by a variety of researchers and research methods (Jensen, et al. 1990). Most of the crop coefficients used by AgriMet, however, were developed using weighing lysimeters at the USDA Agricultural Research Service Research Center in Kimberly, Idaho. Application of these crop coefficients requires, at a minimum, knowledge of the emergence date (or green up date, in the case of perennial plants) for each crop in the vicinity of each weather station. Local contacts (such as county extension agents, crop consultants, or producers) provide this input each spring in order to calibrate the AgriMet crop models to local conditions for that year. The result is a table of daily ET for each crop grown in the vicinity of each AgriMet station (Table 1).

Table 1. Daily AgriMet Crop Water Use Chart

CROP	START DATE	DAILY CROP WATER USE-(IN) PENMAN ET - JUL				COVER DATE	TERM DATE	SUM ET	7 DAY USE	14 DAY USE
		2	3	4	5					
Alfalfa	501	0.35	0.32	0.29	0.23	625	925	9.3	2.0	3.3
Pasture	420	0.24	0.22	0.20	0.16	610	925	8.1	1.4	2.3
Lawn	420	0.28	0.26	0.23	0.18	601	925	9.9	1.6	2.7
W Grain	415	0.35	0.32	0.29	0.23	625	815	12.1	2.0	3.3
S Grain	520	0.34	0.31	0.29	0.23	801	901	5.6	2.0	3.2
Potato	620	0.12	0.12	0.11	0.09	815	1015	1.2	0.7	1.1

DISSEMINATION OF AGRIMET INFORMATION

There are five major products provided by the AgriMet program:

- A table of daily ET values for the last four days for a reference crop (Alfalfa) and specific crops grown in the area. This table includes a 7-day, 14-day, and growing season ET total (see Table 1).
- A table of current weather observations from each AgriMet station, updated hourly.
- A table of summary weather parameters for the last 5 and 10 days for each station.
- A summary of ET for each day of the growing season for each crop grown in the vicinity of each station.
- Historical weather and crop water use data for all stations for the entire period of record.

All of these products are available from Reclamation's AgriMet website at http://www.usbr.gov/pn/agrimet. Information for the Great Plains AgriMet program (east of the continental divide in Montana) is available at http://www.usbr.gov/gp/agrimet. Several local newspapers in the region publish AgriMet crop water use during the growing season, providing an additional means of local dissemination. AgriMet information is further distributed to the user by county extension agents, producer cooperatives, and crop consultants.

USES OF AGRIMET PRODUCTS AND INFORMATION

AgriMet crop water use information is integrated into various on-farm technical assistance programs by local agricultural consultants, the Cooperative Extension Service, and the USDA Natural Resources Conservation Service. As competition for limited water supplies increases - as well as the cost of pumping for irrigation - farmers are turning more and more to scientific irrigation scheduling.

The most common method for irrigation scheduling is known as the "checkbook method," accounting for deposits and withdrawals to the soil moisture balance. For this procedure, the farmer must first know the plant root depth and water holding capacity of his soil. This information is typically available from detailed soil surveys of the area, or from site specific soil tests. After each irrigation during the growing season, the farmer tracks the daily crop specific ET, available from AgriMet. When the cumulative water use equals the Management Allowable Depletion (MAD) for that crop, it's time to irrigate again. Specific knowledge of the irrigation system, combined with ET information from AgriMet, allows a farmer to apply the right amount of water at the right time for optimum crop production. Not only does the farmer typically realize savings in water and pumping costs, but reduced leaching results in reduced costs for fertilizer, herbicides, and pesticides. Various agricultural consultants have reported water and power savings ranging from 15 to 50 percent through the use of AgriMet supplied ET data (Dockter 1996). Some irrigators have reported real savings of as much as $25 per acre in pumping costs after using AgriMet ET data to schedule their irrigations (Palmer 2004). Indirect benefits of scientific irrigation scheduling include potential reduction in non-point source surface water pollution (through reductions in nutrient and chemical laden irrigation tail water) as well as protecting ground water supplies through reduced leaching of agricultural chemicals.

AgriMet ET information is being extensively used by irrigators for on-farm irrigation water management. In a study conducted for BPA, "on-line services, primarily AgriMet, are the most commonly used source for obtaining this (ET) information and account for 45 percent of cases. These figures, however, under-represent the actual use of ET information, particularly from AgriMet, since they do not take into account cases where commercial irrigation service providers provide this data" (Kema-Xenergy, Inc. 2003).

Through scientific irrigation scheduling, AgriMet offers significant opportunities for irrigators to reduce their use of limited irrigation water supplies. There are financial incentives to do so, beyond just the costs of water and the power required to move it. For example, in a case study conducted by Oregon State University (English 2002), an economic analysis was conducted on a 125 acre center pivot of potatoes in Washington supplied by a pump with 700 feet of total lift. Assuming 19 percent excess water use (a typical value, according to the study), and a low sensitivity to the excess water (resulting in a 3 percent yield loss), the extra costs to the farmer included:

Energy Cost:	$ 1,490
Nitrogen Leaching:	$ 5,625
Yield Reduction:	$ 10,890
Total Cost:	$ 18,005

In the Lake Chelan area of Washington, the local irrigation district uses AgriMet data for site-specific irrigation scheduling (Cross 1997). Manual soil moisture measurements are taken weekly at 2-4 sites per orchard in over 60 fruit orchards in the area. Daily AgriMet data is used to monitor the crop water use between field measurements. The soil moisture is plotted on a time series graph, showing soil moisture content at several depths through the growing season. When the AgriMet ET data indicates that the soil moisture has dropped to the management allowable depletion level, the producer irrigates the orchard. The next field measurement shows the new soil moisture levels, and the daily consumptive use values from AgriMet are systematically subtracted from the soil moisture levels until the next irrigation is scheduled. This process is repeated throughout the growing season, and updated information is provided to each producer on the same day the soil moisture measurements are taken.

AgriMet weather data are used for a variety of applications in addition to ET computation, and requests for current and historical weather information from the AgriMet network are common. Agricultural producers depend on wind speed and direction for scheduling such practices as field burning and pesticide applications. Weather data is used by state environmental quality regulators for investigating pesticide application and ground water contamination issues. The National Weather Service uses AgriMet weather data for short term forecasting and forecast verification. Several electric utilities use the weather information to forecast daily energy requirements, including peaking power. University researchers frequently use AgriMet data for a variety of applications, ranging from regional consumptive water use modeling to locating new orchards. ET information is being used by other agencies, such as the National Resources Conservation Service, to document compliance with irrigation water management practices on individual farm tracts. Increasingly, ET information from weather station networks is being used in water rights management by state water resource agencies.

SUMMARY

In the early 1980's Reclamation partnered with BPA to develop a network of automated agricultural weather stations in the Pacific Northwest. From the original three sites installed in 1983, the AgriMet system has now grown to over 90 sites in Idaho, Oregon, Washington, Montana, Wyoming, and California. Reclamation has developed partnerships with over 25 federal, state, and private interests to help fund the operation of the network.

AgriMet stations collect the weather data required for modeling crop ET and transmit this information via satellite to Reclamation's regional office in Boise, Idaho. Every day during the growing season, crop water use charts are developed for crops grown in the vicinity of each AgriMet weather station. This information is available daily through the Internet and is also published in many local newspapers throughout the region. The information is used by federal and state agencies, conservation districts, irrigation districts, extension agents, agricultural consultants, corporate farms, and individual irrigators for water management purposes. The weather data collected is also used for a wide variety of other applications. A rigorous field calibration and maintenance program, and data quality assurance program ensures a high level of data quality and integrity.

Competition for limited water resources is increasing, cost of irrigation water and pumping is rising, and concerns for surface and ground water quality are heightening. In response to these factors, scientific irrigation scheduling is becoming more commonplace. AgriMet is providing the information required to meet these challenges in the Pacific Northwest.

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In Defense of Irrigated Agriculture

Michael F. Dowgert Ph. D.

Irrigated agriculture is one of the most critical human activities sustaining civilization. The current world population of 6.8 billion people is sustained in a large part by irrigated agriculture. USDA statistics show that 17% of cultivated crop land in the United States is irrigated. Yet this acreage produces nearly 50% of total US crop revenues. According to the FAO the approximate 1,260 million ha under rainfed agriculture, corresponding to 80% of the world's total cultivated land, supply 60% of the world's food; while the 277 million ha under irrigation, the remaining 20% of land under cultivation, contribute the other 40% of the food supplies. On average, irrigated crop yields are 2.3 times higher than those from rainfed ground. These numbers demonstrate that irrigated agriculture will continue to play an important role as a significant contributor to the worlds food supply.

Water is increasingly in the headlines and irrigated farmland is increasingly to blame. Government subsidized "cheap water" from century old dams and water projects are not viewed a foresight but as taxpayer subsidies to farmers dismissing the positive effect on food supply and prices. Farmers are blamed for maximizing yield at the expense of natural resources as much a criticism of capitalistic philosophy as agriculture. The fact is that today's farmers are producing more food on less land than ever before. Given current trends in population growth and the loss of prime agricultural land to development this trend must continue if we are to maintain an adequate food supply for the world.

The critical environmental vagary farmers have to deal with is precipitation. Other environmental factors such as temperature, sunlight even insects and disease are far more regular. Thus Irrigation is a powerful mitigator of main environmental risk associated with farming. To this end farmers in drought prone areas make large investments in irrigation. The risk mitigation provided by irrigation goes beyond simple economic advantage to the farmer. Irrigation allows for a more consistent food supply and higher productivity. Recent studies have shown increased CO_2 sequestration, reduced N_2O emissions and more efficient fertilizer use associated with irrigation. The evidence in support of irrigated farming is compelling.

A) Drought and Famine

The causes of famine in the world are complex, often involving economic, political, and biological factors. Each of these factors paints the cause of famine with its own perspective.

Economically, famine is the failure of the poor to command sufficient resources to acquire essential food. The great famine in Ireland which began in 1845 occurred even as food was being shipped from Ireland to England because the English could afford to pay higher prices. The 1973 famine in Ethiopia also occurred as food was being shipped out of Wollo, the center of the famine, to Addis Abba because the capital city could afford to pay more.

Political causes of famine occur because of war, violence or poor public policy. The citizens of the social dictatorships of Ethiopia and Sudan in the 1970's and early 1980's suffered huge famines while the democracies of Zimbabwe and Botswana avoided them in spite of having worse drops in the national food production. This was done through the simple step of creating short term employment for the worst affected groups.

Biologically, famine is caused by the population outgrowing its regional carrying capacity to produce food resources. The failure of a harvest or the change in conditions such as drought can create a situation whereby large numbers of people live where the carrying capacity of the land has dropped radically. Interestingly, at a time when "industrial agriculture" is perceived as a villain, even portrayed as destroying the planet, famine due to crop failure is most often associated with subsistence agriculture, that is where most farming is aimed at simply supplying enough food energy to survive. This means that for farming to provide sufficient food it must be economically satisfying to the farmer not just in good years but year in and out.

Famine records indicate that farm programs that subsidize production may have a positive effect on famine reduction. Europe and the United States have not faced widespread famine due to crop failure in the past 200 years. Up until the middle of the 20th century Africa was not considered to be famine prone. Famine in Africa increased as the economics of agricultural pursuits has become less profitable. Africa does have an ample share of drought, soil problems, crop diseases and especially civil unrest and associated land issues. This has resulted in agrarian life to be uneconomic, and in some regions, fatal. It is the lack of this security that holds most of the blame for African food issues. Long term land and crop security could do much to relieve this.

Crop failures, whether due to natural or man made conditions, have been associated with famine since recordkeeping began. Manmade conditions most frequently include war, particularly attacks on land and farmers meant to starve the local populations. Natural crop failure occurs because of plant disease, such as occurred during the great potato famine, insects such as locusts and, most frequently, drought. Irrigated agriculture provides a buffer against crop failure due to drought.

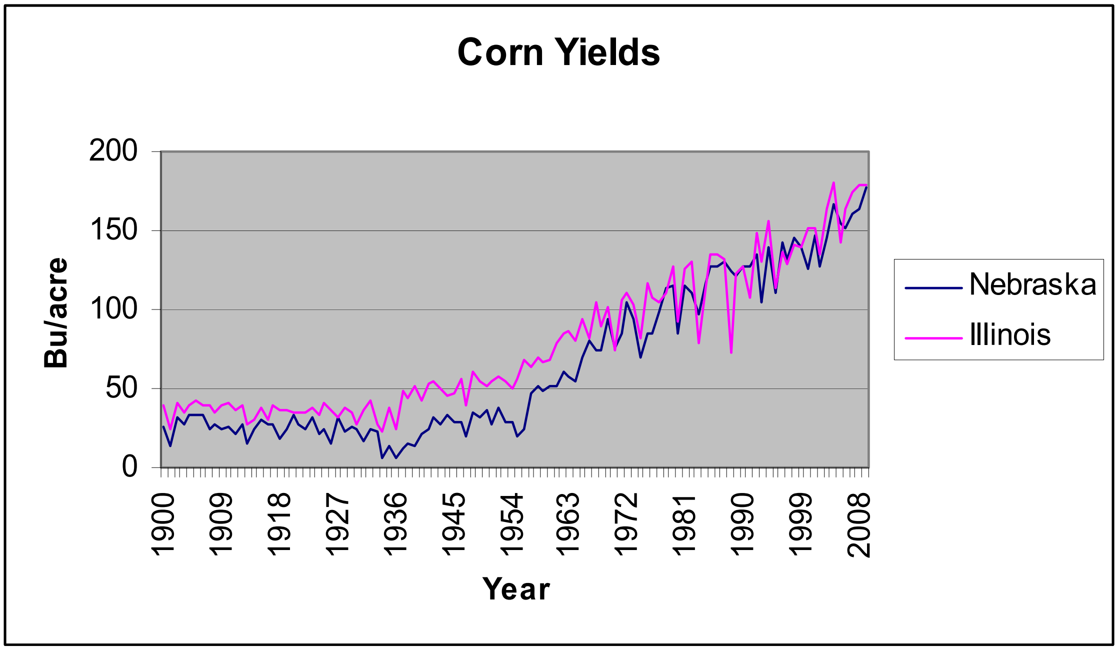

Figure 1. USDA corn yields data for Nebraska and Illinois. In the year 2007 Nebraska had over 80% irrigated corn acres while Illinois had less than 5% irrigated corn acres.

Corn yields from 1900 to 2008 was compared for the rain irrigated state of Illinois averaging over 30 inches per year rainfall and the dryer state of Nebraska with less that 15 inches rainfall on average. In addition, over the last 30 years irrigation has increases in Nebraska from 30% of planted corn in 1966 to over 80% of planted corn in 2008.

The yield data in Figure 1 can be roughly divided into three distinct segments. The relatively constant yields of 30 to 40 bushels/ acre that occurred from 1900 to 1933 covers the period when corn varieties were open pollinated. The rise in corn yields from the 1930's until the 1960's occurs concomitantly with the increased use of double cross hybrids during this time. The more rapid increase in yields from the 1960's until present day corresponds to the introduction of single cross hybrids.

A closer look at each segment offers some insight into the factors affecting corn yields in these two different environments. Figure 2 looks at the trends in the era from 1900 to 1930 when farmers only had access to open pollinated corn varieties. During this period there was some flood irrigation in Nebraska but it accounted for less than 10% of total corn acreage. During this period the total acreage planted to corn in these states was some 20% higher than that planted today, over 9 million acres in Nebraska and 13 million acres in Illinois. On average Illinois yielded about 10 bushels more per acre than Nebraska. It is clear from the data that the yields from Nebraska are more variable than the yields from Illinois. It is not possible to correlate yield to specific rainfall events because the timing of the rain is critical to corn yields but it can be said that greater variability in yields observed in Nebraska as opposed to Illinois can be related to the greater variability in rainfall found in this region.

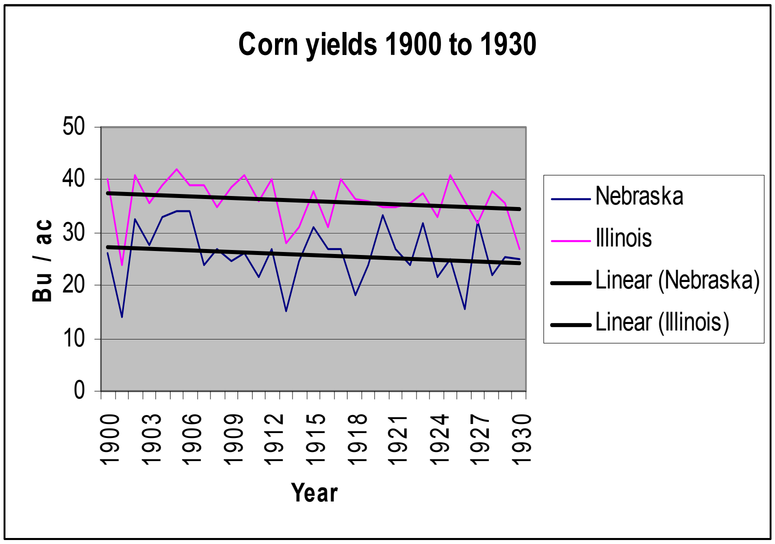

Figure 2. USDA statistics of corn yields in Illinois and Nebraska from 1900 to 1930.

The period from 1930 to 1935 corresponds to the drought that caused the dust bowl in the Great Plains. The collapse of corn yield in Nebraska is evident in Figure 1. The drought during this time did impinge upon Illinois but was much less severe in this region. This is reflected in the corn yield data. Following this period yields began to increase due to advanced genetics and better crop practices developed by the land grant universities (Figure 3.).

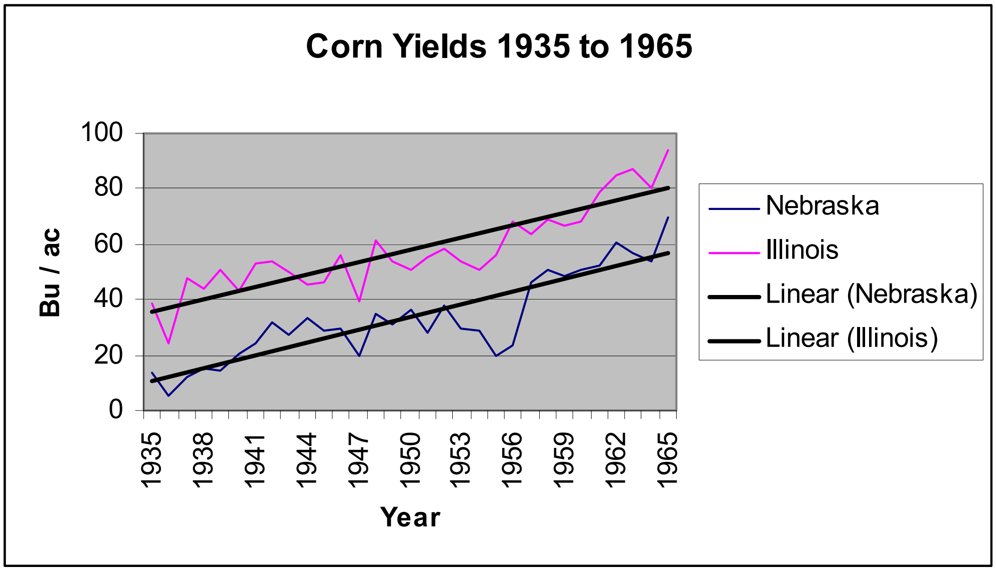

Figure 3. USDA statistics of corn yields in Illinois and Nebraska from 1935 to 1965.

Interestingly, the approximate 10 bushel higher yield observed for corn grown in Illinois compared to Nebraska was maintained during this period. Yield reductions due to a significant drought from 1952 to 1957 are obvious in this data. As was seen in the period 1930-1935, the effect was more pronounced in Nebraska relative to Illinois due to more variable precipitation in the more western state.

The period from 1965 to present is marked by a massive increase in irrigation in Nebraska. In 1966 there were 3 million irrigated acres while in 2002 there were 8 million acres. Over this time the area devoted to corn in the state of Nebraska was constant at a little over 9 million acres. This period also marked the largest increase in yields in both irrigated Nebraska and non-irrigated Illinois. This yield increase is often attributed to the "green revolution" of better fertilization methods along with improved varieties and crop protection chemicals. The reality is that the green revolution started as early as the turn of the century and started to take off in the 1930's. The large yield increases seen since the 1960's was the mainstreaming of the yield increasing technologies due to increased farm investment.

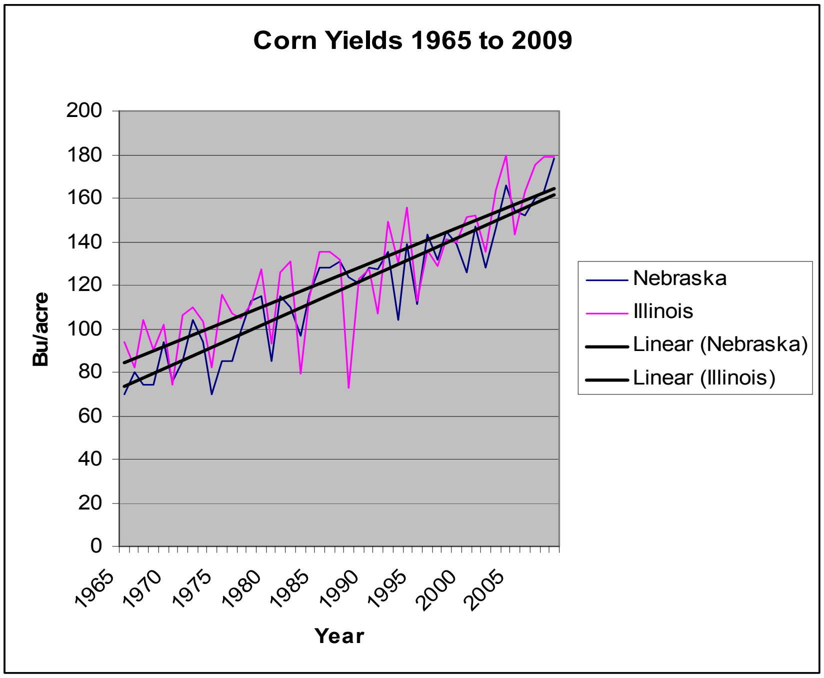

Figure 4. USDA statistics of corn yields in Illinois and Nebraska from 1965 to 2008.

The data in Figure 4 indicate that the average yield for the state of Nebraska is for the first time approaching the yield for Illinois. This suggests that irrigation, or the lack of it, was entirely responsible for the difference in yields between the two states. In addition over this time period the variability in yields is more pronounced in Illinois. A regression analysis confirms this giving an R squared for Nebraska of 0.85 while for Illinois a 0.68. This suggests that irrigation also reduces variability in yield.

B) Productivity of Irrigated land

According to the FAO, average crop yields for irrigated acres are 2.3 times those from rainfed areas. The actual yield increase will vary according to the region and the crop. In Nebraska the yield boost attributed to irrigation between 1992 and 2007 ranged from 10% for sorghum in 1998 to 268% for corn grown in 2002 (Table 1.) Corn wheat and alfalfa exhibited the greatest response to irrigation while sorghum and soybeans had a lower positive response. The high productivity of irrigated agriculture allows fewer acres to feed a larger proportion of the global population. Increasing productivity per acre is critical as farmland acreage continues to be converted to residential property.

Yield per Acre of Major Crops in Nebraska

	Corn for Grain (Bu.)		Sorghum Grain (Bu.)		Wheat (Bu)		Soybeans (Bu.)		Alfalfa Hay (Tons)	
	irrigated	non-irrigated	irrigated	non-irrigated	irrigated	non-irrigated	irrigated	non-irrigated	irrigated	non-irrigated
1992	144	117	101	93	49	29	45	41	4.5	3.4
1993	111	90	70	58	56	28	41	34	4.1	3.2
1994	153	113	109	97	55	34	53	45	4.5	3.2
1995	130	73	74	57	62	40	42	29	4.4	3.2
1996	156	115	106	94	53	35	50	43	4.8	3.3
1997	151	99	101	80	48	36	51	37	4.5	2.8
1998	161	119	104	94	68	45	51	41	4.8	3.4
1999	159	111	102	91	66	47	51	38	4.6	3.4
2000	154	84	98	69	63	34	50	30	4.5	2.6
2001	173	110	106	83	59	35	53	39	4.7	3
2002	166	62	83	48	63	30	51	29	4.4	2.3
2003	186	82	117	56	67	44	54	31	4.8	2.9
2004	186	134	110	78	66	33	54	40	4.7	2.9
2005	185	108	113	84	60	37	59	43	na	2.4
2006	185	101	109	77	67	32	59	42	na	2.1
2007	181	125	117	96	58	40	55	47	na	2.4

Table 1. Yield of irrigated and non-irrigated crops in Nebraska 1992 to 2007

The need for increasing yields on increasingly poor quality land is becoming more pressing as land development for housing increases. The United States looses two acres of prime farmland every two minutes. From 1992 to 1997, six million acres of agricultural land was converted to developed uses. This represents an area the size of Maryland. Much of this land is prime land.

The rate of conversion of prime land was 30% faster than for non prime land. This results in more marginal land being put into production. In addition, most of the development is occurring in areas that receive significant natural rainfall. Of the top 12 states losing prime farm land only one, Texas, significantly relies on irrigation. This development forces more production into irrigated lands increasing the pressure on water supplies.

Development is also pushing agriculture to more marginal lands. Flat, well drained land is considered prime land for farming. It is also the least expensive to develop into housing and commercial properties. The Southern California Central Valley averages 10 to 15 inches of rainfall a year while the coastal valley including Watsonville and Salinas averages twice that amount. Yet housing is pushing vegetable production out of the relatively wet coastal valley to the dryer central valley where more irrigation is required. In another example, most of the best farmland in New Jersey is now covered by houses. This is occurring at a time when "buy local" is being promoted as the most sustainable food option. Loss of arable land is increasing as the world population gets wealthier. The general fact is that agricultural land and water use cannot compete economically with industrialized or residential uses. As discussed earlier farming must result in economic benefit for the farmers or crop production will not keep up with demand and food shortages will result. Water use policy must also include land use policy as part of the conversation.

Prime Acres Lost

State	87-92	92 -97
TX	234,300	332,800
OH	146,400	212,200
GA	110,900	184,000
NC	167,100	168,300
IL	67,900	160,900
PA	109,700	134,900
IN	75,100	124,200
TN	87,200	124,000
MI	72,700	121,400
AL	50,200	113,800
VA	59,800	105,000
WI	54,200	91,900
NY	36,900	89,100
SC	52,600	86,200
CA	73,800	85,200

Table 2 Farm acres lost by state

C) Irrigated Agriculture and Environmental Quality

Researchers are beginning to consider the effect of irrigated agriculture on greenhouse gasses and air quality. Researchers in Idaho looked at the organic carbon stored in soils having long-term cropping histories of various crops. They found that irrigated pasture and irrigated reduced till cropping sequestered more carbon in the soil than native rainfed vegetation. Full tillage irrigated crops sequestered the least carbon. The authors concluded that if worldwide irrigated acreage were expanded 10% and the same amount of rainfed land were converted to native grassland that 5.9% of the total carbon emitted in the next 30 years could be sequestered. Studies of the effects of irrigation on the environment are new but show promise.

Another study compared drip and furrow irrigation relative to CO_2 and N_2O emissions. The CO_2 emissions were lower in drip irrigated compared to flood irrigated treatments but the differences were small (4%). More significantly, of the 100 pounds of N/acre added as fertilizer 18% was lost as N_2O in the furrow irrigated treatments compared to only 4% in the drip irrigated treatments. Although both gases are significant contributors to global warming N_2O is 300 times more potent than CO_2. Other studies indicate a positive relationship between irrigation and fertilization efficiency, supporting the conclusion that efficient irrigation reduces N_2O emissions.

Rainfall leaches nutrients from the soil. This is why, even in areas of high rainfall such as Florida, many growers practice plasticulture, the practice of using plastic mulch to better manage the soil environment. Strawberries and tomatoes are often grown in beds that are covered with plastic mulch. In addition to creating a clean surface for the fruit, this mulch prevents the natural heavy rains from saturating the soil and leaching out the applied nutrients. Irrigation, often drip irrigation, is then used to supply the necessary water.

Studies conducted in West Texas from 2000 to 2007 revealed that recovery efficiency of added N fertilizer ranged from a minimum of 12% in furrow irrigated fields to a maximum of 75% in fertigated fields. The relationship of total N uptake (pounds/acre) relative to yield in bales for all irrigation systems indicates that a bale of yield requires 40 pounds N per acre regardless of the treatment. Thus a furrow system that is only 12% efficient must apply 300 lbs N/bale/acre compared to 53 lbs N/bale/acre for a drip system that is 75% efficient. This saves money, potential runoff and N_2O emissions.

D) Irrigated Agriculture and Business planning

The risk associated with Agricultural production can be divided into three components

1) Systemic Risk – this is the risk associated with lost production most often associated with the weather, particularly rainfall but also insects and disease
2) Market risk – that associated with crop prices
3) Credit risk – usually associate with the low value of farm land relative to the cost of production.

The systemic risk is mitigated through the implementation of a crop insurance program, crop protection program, nutrient management program and irrigation program. The first three are usually treated as variable expenses while the irrigation system is a capital expense. The United States offers an excellent laboratory for considering the systemic risk associated with irrigated agriculture. In the Western arid states most crops cannot be grown without irrigation so irrigation is a necessary component of production. As you move East to the high plains, most crops can be successfully grown using natural rainfall but irrigation is necessary to obtain maximum yields (see Table 1). In this case there are measurable benefits and risks to choosing or not choosing to irrigate. The actual choice is many times dictated by incentives and subsidies but the result is more consistent high yields. Table1 indicates the risk for dryland farming of corn in Nebraska ranges from a minimum of 21 bushels to a maximum of 102 bushels per acre. The average difference is 58 Bu. This yield increase significantly reduces the risk associated with production in this region which is why over 80% of Nebraska farmland is irrigated.

Moving east of the Mississippi, rainfall is usually adequate for crop product except for exceptionally dry years. The decision then is whether to invest in irrigation as an insurance against 2 or 3 out of 10 dry years. This type of irrigation insurance is strongly dependent on the price of the irrigation system.

Market risks are mitigated through various selling contracts, futures, cash sales and hedge contracts. These instruments, while complicated, add significant upside potential to the farmer.

The credit risk of farming is usually associated with lenders but can affect farmers looking for funds to make significant investment in equipment such as irrigation systems.

In addition to risk mitigation, irrigation also allows for a more consistent yield year after year. This was shown to be true in irrigated Nebraska compared to Illinois (Figure 4). More consistent yields allow for more consistent application of market risk management tools such as futures and hedges. Also, the regular income associated with more consistent yields also improves the credit risk position of farmers seeking credit. This results in lower rates and better profitability. Finally consistent yields and revenues contribute to better business planning on a longer time scale, resulting in increased resource efficiencies.

Conclusion

Irrigated agriculture is critical to maintaining and growing the world’s food supply as population grows. Analysis of yield data from Nebraska and Illinois indicates that irrigation mitigates the effects of drought, the number one environmental factor reducing yields. In addition irrigation results in more consistent yields which allow for better business planning particularly with regard to market dynamics. Prime agricultural land is being lost to development at an astonishing rate. Irrigation improves agricultural productivity particularly on marginal ground. This is necessary to meet future food needs in the face of reduced growing area. Irrigation may also help sequester carbon dioxide, reduce N_2O emissions from the soil and reduce fertilizer needs. This is not to say that water supplies, both ground and surface, need not be managed. Water must be available for people, industry, nature and food. Food is critical because it is the abundance of food that sustains people and industry and allows us the freedom to consider and preserve nature.

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AG TO URBAN WATER TRANSFERS:
MITIGATION OF NEGATIVE EFFECTS VOLUNTARY OR REQUIRED?

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ABSTRACT

Agricultural and urban representatives to Colorado's Arkansas Basin Roundtable spent two years with a neutral facilitator hammering out a set of guidelines they could all agree to in answer to the question: "IF water is to be transferred from agriculture, how can we do it with the least damage to the environment and rural communities?" How the template they developed should be used is the basis of ongoing dialogue. Should the guidelines become the basis for regulation, or should they just be seen as educational? Should third parties to a transfer, such as rural communities, have a voice at the table or should transfers be a matter solely between willing buyer/willing seller? The presenter of this session, who served as the facilitator, will engage the IA audience in dialogue about this difficult question which is increasingly being asked in communities around the country.

BACKGROUND FOR DIALOGUE

"Colorado will see a significantly greater reduction in agricultural lands as municipal and industrial water providers seek additional permanent transfers of agricultural water rights to provide for increased urban demand."

That sentence from the 2004 Statewide Water Supply Initiative (SWSI) sparked the debate which led to a group of rural and urban stakeholders from Colorado's Arkansas River basin in the southeast quadrant of the state to spend two years trying to come to consensus about how to deal with the downside of such transfers.

Despite their differences, the stakeholders were mutually concerned about the effects agricultural to urban water transfers might have on third party interests including rural communities and the environment. They put more than 1400 hours of work into trying to answer the question: "If water is going to be transferred from agriculture, how can it be done right—with full awareness of the issues to be resolved?"

The Arkansas Basin Roundtable is one of nine created by the Colorado legislature to address the projected gap by the year 2030 between a watershed's water supply and its demand. In the fall of 2006, Lawrence Sena, Mayor of Las Animas, took the microphone at a meeting of the Arkansas Basin Roundtable and said, “Some of us have put together a set of guidelines we would like for the roundtable to adopt—guidelines for cities to follow if they are going to transfer water from agriculture.” Urban water managers on the roundtable didn’t see things quite the same way, particularly the call for urban communities to control their growth. Thus began the work of the Water Transfer Guidelines Committee. State water leaders cited it as an exemplary process: stakeholders on opposite sides of the table working out their differences to cooperatively tackle a significant issue with high stakes for the Arkansas Basin, the state of Colorado, and indeed the entire western United States.

In September, 2008, the committee presented to the Arkansas Basin Roundtable a report of their work, *Considerations for Ag to Urban Water Transfers*, which includes guidelines to be taken into account if and when water is transferred from agriculture. The guidelines offer a number of mitigation measures that could be used, such as payments in lieu of taxes to offset school district revenue decreases in rural areas, or an urban community providing economic development assistance to a rural community. The committee did not, however, attempt to conclude whether such mitigation measures should be legislated or whether it should be voluntary.

The Arkansas Basin Roundtable accepted the report, praised the work of the committee, and spent several meetings debating how the report should be used. Most roundtable member points of view center around one of the following:

1. These guidelines for ag to urban transfers should be the basis for some sort of regulatory approach. Otherwise we are only giving lip service to the rights of third parties, such as rural communities, who are affected by these transfers.

2. The guidelines are fine, but they should remain just that—guidelines. Nothing should come between willing buyer, willing seller when it comes to transfer of water from agriculture. We should not try to have mitigation become law.

3. Transfers are going to happen, and these guidelines are important for raising the consciousness about the effects on agriculture and rural communities. However, rather than promote or fight transfers, we should turn our attention now to how we could come up with incentives for agriculture to keep water in the valley. What creative approaches could be considered?

The report has been the topic of much discussion statewide, among groups such as the Interbasin Compact Committee, Colorado Water Congress, and the Colorado Agricultural Water Alliance. Recently, a Colorado state legislator referred to the report in a press release in which he announced that he is formulating legislation to "provide an incentive for urban areas to provide for the future needs of rural communities in water transfers." His bill would allow judges in water courts to consider mitigation on transfers of water. He said, "The bill would be open to all types of mitigation, a question that the Arkansas Basin Roundtable addressed in its report, *Considerations for Agriculture to Urban Water Transfers*."

QUESTIONS FOR DIALOGUE

Which of the three points of view expressed by members of the Arkansas Basin Roundtable do you ascribe to? Or do you have an entirely different point of view, or a hybrid point of view? If you were in a sinking boat with a group of water stakeholders who were evenly split on this issue, what could you offer that in fifteen minutes you think everyone could agree on? Would that be useful to the state legislator trying to get his legislation passed? If you had more than fifteen minutes (the boat had a very slow leak and you had plenty of food onboard) what process would you use to try to bring your fellow boaters to consensus?

REFERENCE

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Determination of Kinetic Energy Applied by Center Pivot Sprinklers

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Abstract. *The kinetic energy of discrete drops impacting a bare soil surface is generally observed to lead to a drastic reduction in water infiltration rate due to soil surface seal formation. Under center pivot sprinkler irrigation, kinetic energy transferred to the soil prior to crop canopy development can have a substantial effect on seasonal runoff and soil erosion. In the design of center pivot irrigation systems, selection of sprinklers with minimum applied kinetic energy could potentially minimize seasonal runoff and erosion hazard. Size and velocity of drops from five common center pivot sprinklers were measured using a laser in the laboratory. The data were used to calculate kinetic energy transferred to the soil by each sprinkler on a center pivot irrigation system lateral with 2.5 m spacing between sprinklers. Specific power, which represents the rate that kinetic energy is transferred to the soil as a function of distance from a sprinkler and analogous to a sprinkler radial water application rate distribution, was used to estimate actual kinetic energy transferred to the soil by overlapping specific power profiles of sprinklers equally spaced along a center pivot lateral. Kinetic energy of irrigation sprinklers has traditionally been characterized using area weighted kinetic energy per unit drop volume. This characterization was found not to be correlated to actual kinetic energy transferred to the soil by the sprinklers. The results demonstrated that sprinklers with the smallest drop sizes do not necessarily transfer the least kinetic energy per unit depth of water applied. Conversely, sprinklers with the largest drop sizes do not necessarily transfer the greatest kinetic energy to the soil.*

Keywords. Sprinkler irrigation, Center pivot, Infiltration, Runoff, Kinetic energy.

Introduction

When discrete water drops impact a bare soil surface a drastic reduction in water infiltration rate is generally observed due to compaction, aggregate destruction, soil particle detachment, dispersion, and in-depth wash-in of fine particles. These physical processes reduce surface soil porosity and pore size distribution to create a soil surface seal with reduced hydraulic conductivity that expands in size and depth with time (Assouline and Mualem, 1997). The effect soil surface seal formation has on water infiltration rate has been studied by Agassi et al. (1984,1985), Thompson and James (1985), Mohammed and Kohl (1987), Ben-Hur et al. (1987) and Assouline and Maulem, (1997). These studies have shown that kinetic energy of discrete drops impacting a bare soil surface is a primary factor in determining the reduction in water infiltration rate due to soil surface sealing. Much of the research on soil surface sealing has focused on rainfall conditions but the same processes occur under sprinkler irrigation (von

Bernuth and Gilley, 1985; Ben-Hur et al., 1995; DeBoer and Chu, 2001; Silva, 2006). Soil surface seal formation leading to a reduction in water infiltration rate in combination with high water application rates under center pivot sprinkler irrigation exacerbates potential runoff and erosion hazard.

The effect kinetic energy applied by center pivot sprinklers has on infiltration and runoff is well known in the center pivot sprinkler irrigation industry. Over the past two decades, center pivot sprinkler manufacturers have continued to develop sprinklers that reduce peak water application rates and droplet kinetic energy as a means to sustain water infiltration rates and reduce potential runoff and erosion hazard. Consequently, there are numerous center pivot sprinkler choices available to the center pivot sprinkler irrigation system designer and producer but limited quantitative information that relates these choices to performance in regards to infiltration, runoff and erosion. Kincaid (1996) developed a model to estimate kinetic energy per unit drop volume from common sprinkler types as a function of nozzle size and operating pressure to be used as a design aid in selecting center pivot sprinklers. DeBoer (2002) evaluated the kinetic energy per unit drop volume from select moving spray-plate sprinklers for center pivot irrigation systems and developed a model of kinetic energy as a function of spray-plate type, nozzle size and operating pressure. Values of kinetic energy per unit drop volume are largely dependent upon the drop size characteristics of the sprinklers. Sprinklers with relatively large drop sizes have the highest kinetic energy values and sprinklers with relatively small drop sizes have the lowest kinetic energy values. The drop size distribution of a sprinkler has a substantial influence on the wetted diameter and application rate distribution profile. In general, sprinklers with relatively small drop sizes have relatively small wetted diameters and result in higher application rates when application rate pattern profiles are overlapped along a center pivot lateral. Sprinklers with relatively large drop sizes have relatively large wetted diameters and result in lower application rates when application pattern profiles are overlapped along a center pivot lateral. In regards to runoff and erosion, any benefits associated with lower applied kinetic energy from smaller drops are reduced or eliminated due to the higher application rate which often exceeds the water infiltration rate of the soil. Consequently, values of kinetic energy per unit drop volume do not identify an optimum sprinkler selection, and thus have not proved very useful in center pivot sprinkler irrigation system design.

King and Bjorneberg (2009) evaluated runoff and erosion from five common center pivot sprinklers on multiple soils and found significant differences between center pivot sprinkler types of equal flow rates. Estimated values of kinetic energy per unit drop volume from the models of Kincaid (1996) and DeBoer (2002) did not correlate with measured runoff or erosion rates. The objectives of this study was to evaluate the kinetic energy applied to the soil in the center pivot sprinkler experiments of King and Bjorneberg (2009) and compare the results with kinetic energy per unit volume used to characterize sprinkler kinetic energy.

Methods and Materials

Sprinklers used in this study and corresponding operating pressures and nozzle sizes are listed in table 1. Sprinkler types and operating pressures were selected to be representative of field installations on center pivot sprinkler irrigation systems in southern Idaho. Sprinkler nozzle sizes were selected to provide nearly equal flow rates among sprinklers at high and low flow rates at the given operating pressures, based on manufacturer data. The high flow rate nozzle is representative of that found near the end of the lateral on 390 m long center pivot sprinkler irrigation systems in southern Idaho.

Table 1. Sprinklers and corresponding operating pressure, nozzle diameter and flow rate used in study.

Sprinkler	Pressure kPa	Nozzle Diameter mm	Flow Rate* L/min
High Flow Rate			
Senninger I-Wob Standard 9-groove Plate	103	8.33	43.2
Nelson R3000 Brown Plate	138	7.54	42.7
Nelson R3000 Red Plate	138	7.54	42.7
Nelson S3000 Purple Plate	103	8.14	43.5
Nelson D3000 Flat Plate	103	8.14	43.5
Low Flow Rate			
Senninger I-Wob Standard 9-groove Plate	103	5.55	19.8
Nelson R3000 Brown Plate	138	5.36	21.2
Nelson R3000 Red Plate	138	5.36	21.2
Nelson S3000 Purple Plate	103	5.75	21.4

*Manufacturer's published data.

Drop sizes and drop velocities from the sprinklers were measured using a Thies Clima Laser Precipitation Monitor (TCLPM) (Adolf Thies GmbH & Co. KG, Göttingen Germany) (King et al., 2009). The tests were conducted in the laboratory and represent a no wind condition. Drop size and velocity measurements were collected at 1 m increments from the sprinkler. A minimum of 10,000 drops were measured at each measurement location except at the most distal radial location where a minimum of 4,000 drops were measured to save time. Sprinklers were positioned on the end of a drop tube with nozzle discharge directed vertically downward 0.8 m above the laser beam of the TCLPM. Pressure regulators with nominal pressure ratings for the test condition were used to control pressure at the base of the sprinkler. A pressure gauge located between the pressure regulator and sprinkler base was used to monitor pressure during a test. Pressure values were within ±7 kPa of the nominal pressure rating. Specific details of the experimental methods are provided by King et al. (2009).

Radial application rate distributions for the sprinklers were also determined in the laboratory. Catch cans, 15 cm in diameter and 18 cm tall spaced at 0.5 m increments from the sprinkler in one radial direction, were used to collect water. Sprinkler height was 0.8 m above can opening. The duration of each test was 30 to 60 minutes. Water collected in each can was measured using a graduated cylinder. Application rate was calculated based on the diameter of the catch cans and the duration of each test.

Area weighted kinetic energy per unit drop volume, KE_d (J/L), of each sprinkler was computed as:

$$KE_d = \frac{\sum_{i=1}^{R}\left(\frac{\sum_{j=1}^{ND_i}\frac{\rho_w \pi d_j^{\,3} v_j^{\,2}}{12}}{1000\sum_{j=1}^{ND_i}\frac{\pi d_j^{\,3}}{6}}\right)A_i}{\sum_{i=1}^{R}A_i} \tag{1}$$

where R is the number of radial measurement locations, ND_i is the number of drops measured at the ith radial location, ρ_w is the mass density of water (kg/m^3), d_j is the measured diameter (m) of the jth drop, v_j is the measured velocity (m/s) of the jth drop and A_i is the wetted area (m^2) associated with ith radial location. The resulting value represents the average kinetic energy per liter of drop volume applied over the wetted area (Kincaid, 1996; DeBoer 2002).

The specific power, SP (W/m^2), as a function of radial measurement location for each sprinkler was computed as:

$$SP_i = \left(\frac{\sum_{j=1}^{ND_i}\frac{\rho_w \pi d_j^{\,3} v_j^{\,2}}{12}}{1000\sum_{j=1}^{ND_i}\frac{\pi d_j^{\,3}}{6}}\right)\cdot\frac{AR_i}{3600} \tag{2}$$

SP represents the time derivative of kinetic energy per unit area i.e. the rate at which kinetic energy is transferred to the soil surface as a function of radial distance from the sprinkler. SP is sometimes referred to as droplet energy flux (e.g. Thompson and James, 1985). A sprinkler radial SP distribution is analogous to a sprinkler radial water application rate distribution. Just as the depth of water applied by a center pivot sprinkler irrigation system can be determined by integrating with respect to time the composite overlapped sprinkler application rate distribution perpendicular to the sprinkler lateral, the kinetic energy applied by a center pivot irrigation system can be determined by integrating with respect to time the composite overlapped sprinkler SP distribution perpendicular to the sprinkler lateral.

A sprinkler overlap model written in Visual Basic was used to compute the composite water application rate distribution perpendicular to the sprinkler lateral. The sprinkler overlap model used a 0.3 m distance increment in determining the composite water application rate distribution. The sprinkler application rate distributions determined in the laboratory were used in the sprinkler overlap model. The sprinkler application rate distributions were interpolated to 0.3 m distance increments using cubic spline interpolation between catch can measurements. Modeled sprinkler spacing along the lateral was 2.5 m.

Water application depth was determined by numerically integrating the composite sprinkler application rate distribution perpendicular to the sprinkler lateral with time. The time required by the sprinkler lateral to pass over a location and apply 25 mm of water was numerically determined by adjusting the integration time period (sprinkler lateral travel speed).

The sprinkler overlap model was also used to compute the composite SP distribution perpendicular to the sprinkler lateral with time. The SP distribution was determined at 0.3 m increments based on cubic spline interpolation of the SP_i at each *i*th radial measurement location (equation 2). The kinetic energy applied by 25 mm of water application was determined by numerically integrating the composite SP distribution perpendicular to the sprinkler lateral using the same time period required to apply 25 mm of water. Applied kinetic energy per unit volume of water application, KE_a (J/ m^2 mm), was determined by dividing the total applied kinetic energy by the depth of water application (25 mm). Total kinetic energy applied by irrigation can then be determined by multiplying KE_a by the applied irrigation depth.

Results and Discussion

Measured drop size distributions for the five high flow rate sprinklers used in the study are shown in figure 1. The drop size distribution of the D3000 sprinkler had the smallest range in drop size and the smallest maximum drop size (approximately 3.0 mm) of the five sprinklers. Approximately 90% of the applied water volume (d_{90}) was from drops less than 2.0 mm in diameter. The I-Wob sprinkler had the largest range in drop size with a maximum drop size of approximately 5.5 mm in diameter. Although the R3000 red plate and S3000 sprinklers both use 6-groove moving spray-plates, the d_{30} through d_{80} drop sizes of the R3000 red plate sprinkler were slightly smaller than the S3000 sprinkler. This is largely due to the higher pressure used with the R3000 red plate sprinkler. This outcome was unexpected as the S3000 sprinkler is generally considered to provide smaller drops that are less destructive to the soil surface structure with lower operating pressure. The R3000 brown plate sprinkler had a range in drop size similar to the R3000 red plate and S3000 sprinklers. Surprisingly though the d_{10} through d_{98} drop sizes of the R3000 brown plate sprinkler were smaller than for the R3000 red plate, S3000 and I-Wob sprinklers. Based solely on measured drop size distributions and the fact that larger drops possess greater kinetic energy, the relative ranking of the sprinklers would rank the I-Wob as having the greatest potential destructive effect on soil structure and the D3000 having the least potential destructive effect.

Measured drop size distributions for the four low flow rate sprinklers used in the study are shown in figure 2. The relative ranking of the sprinklers based on drop size changed with nozzle flow rate. The R3000 red plate and I-Wob sprinklers have very similar drop size distributions at the low flow rate with nearly the same maximum drop size of approximately 4.5 mm. The S3000 sprinkler has the smallest fraction of water applied over the 1.3 to 3.5 mm drop size and a relatively large fraction of water is applied over the drop size range of 3.5 to 4.1 mm as evident from the steep increase in cumulative volume over this range in drop size. The R3000 brown plate sprinkler has the largest range in drop size with a maximum drop size of approximately 5.2 mm. Based solely on measured drop size distributions the R3000 brown plate sprinkler would have the greatest potential destructive effect on soil structure.

Radial application rate distributions for each of the five high flow rate sprinklers used in the study are shown on figure 3. The I-Wob and R3000 brown plate sprinkler had the largest wetted radiuses of the five sprinklers and the D3000 had the smallest wetted radius. The wetted radius of each sprinkler was correlated with the largest drop size of each sprinkler. The I-Wob and R3000 brown plate sprinklers had the largest drop sizes and hence the largest wetted radiuses of the five sprinklers. These sprinklers had about a one meter greater wetted radius than the S3000 and R3000 red plate sprinklers.

Radial application rate distributions for each of the four low flow rate sprinklers used in the study are shown in figure 4. The I-Wob, S3000 and R3000 red plate sprinklers all have nearly the same wetted radius at the low flow rate. The R3000 brown plate sprinkler has the largest wetted radius, approximately 0.6 m larger, which is consistent with having in the largest drop size distribution and drop size (fig. 2).

Computed KE_d values for each of the five high flow rate sprinklers are shown in table 2. Based on KE_d, the I-Wob had the highest kinetic energy and the D3000 had the lowest. This was expected based on the drop size distributions for the two sprinklers (fig. 1) and the fact that calculation of kinetic energy based on equation 1 is area weighted, which heavily weights the largest drops that travel the farthest from the sprinkler and have the greatest kinetic energy. The relative ranking of the R3000 red and brown plate and S3000 sprinklers based on KE_d were essentially reversed from the ranking based on d_{90} drop sizes. The R3000 brown plate sprinkler, which had the smallest d_{10} through d_{95} drop sizes of the three sprinklers, had the largest KE_d value of the three sprinklers. This was due to the area weighting associated with equation 1. The R3000 brown plate sprinkler had the largest d_{98} to d_{100} drop sizes of the three sprinklers which travel farther from the sprinkler (fig. 3) and are heavily weighted even though the largest drops constitute less than 2% of total sprinkler volume. This outcome suggests that area weighted kinetic energy per unit drop volume is not necessarily a good indicator of kinetic energy transferred to the soil by irrigation sprinklers, but has traditionally been

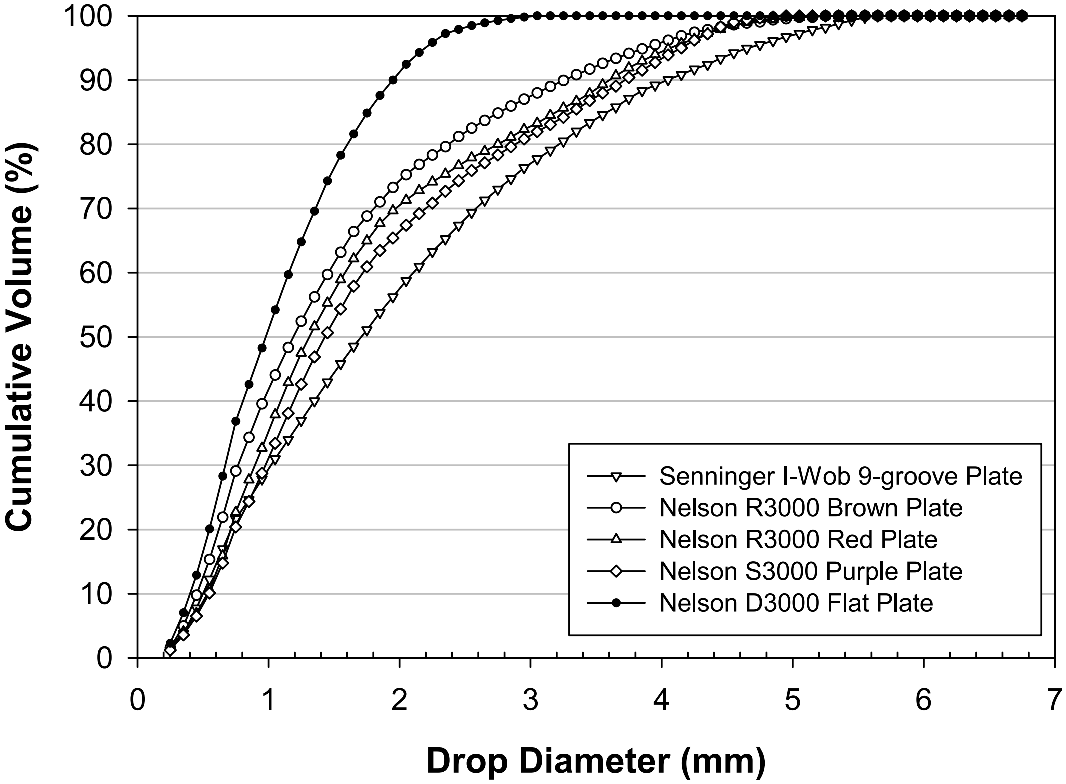

Figure 1. Drop size distribution of high flow rate sprinklers used in study.

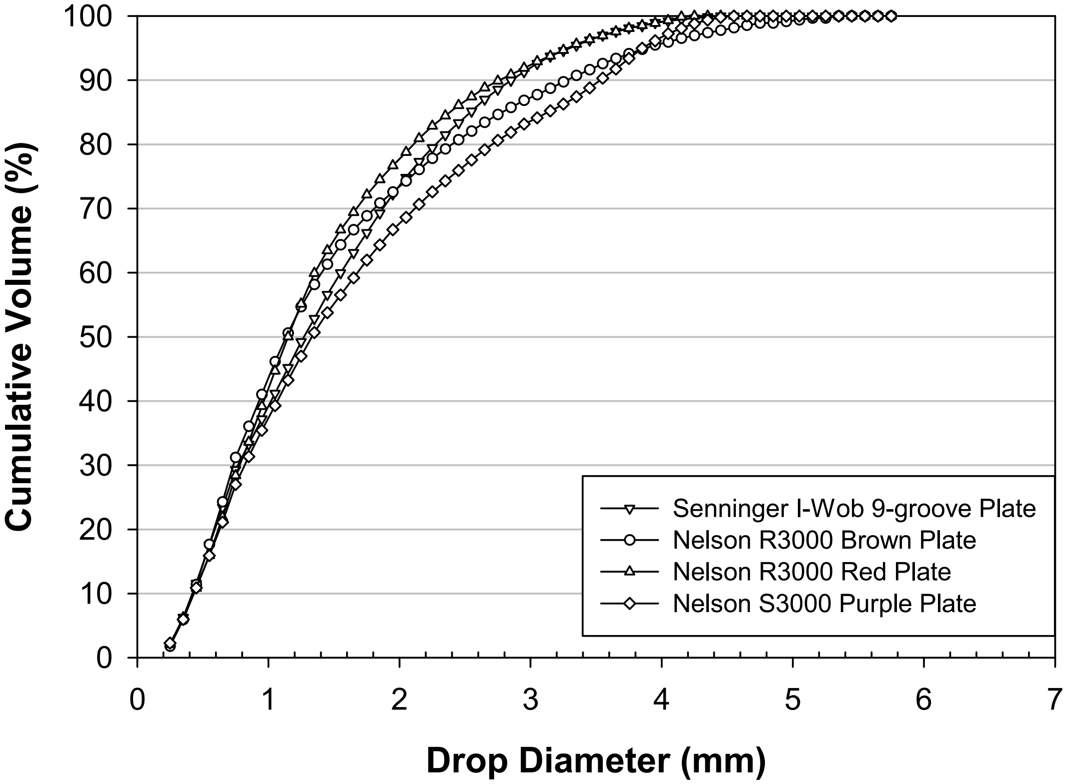

Figure 2. Drop size distribution of low flow rate sprinklers used in study.

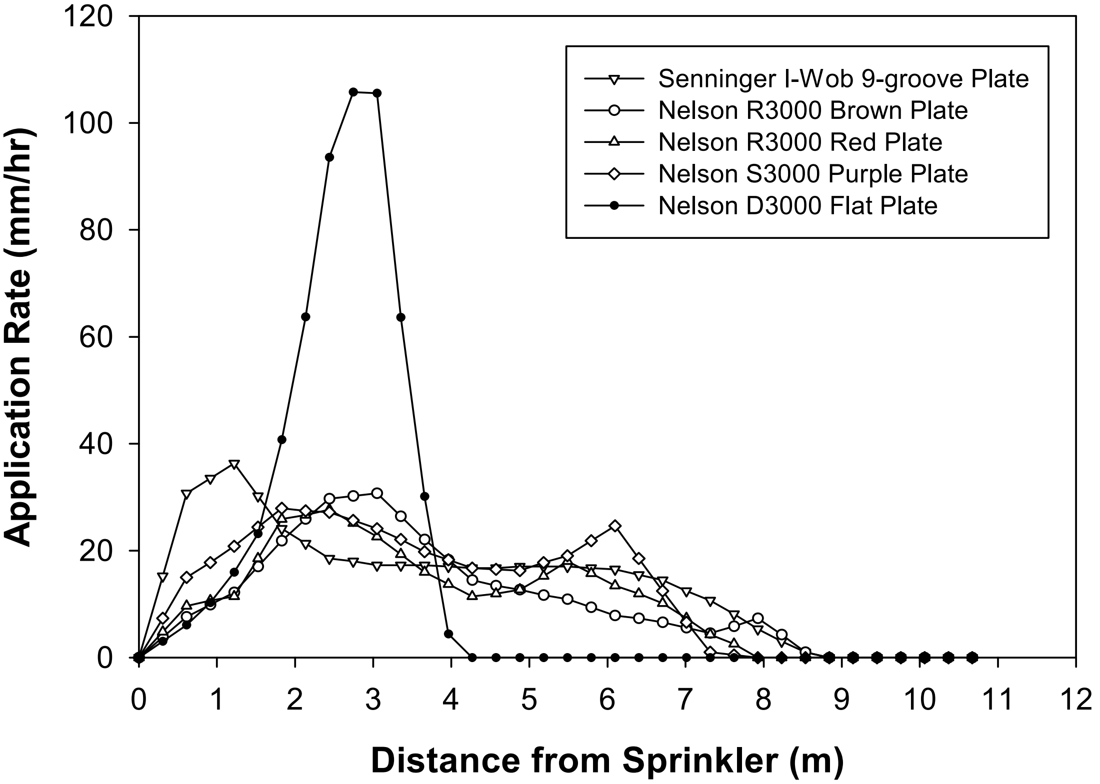

Figure 3. Radial application rate of high flow rate sprinklers used in study.

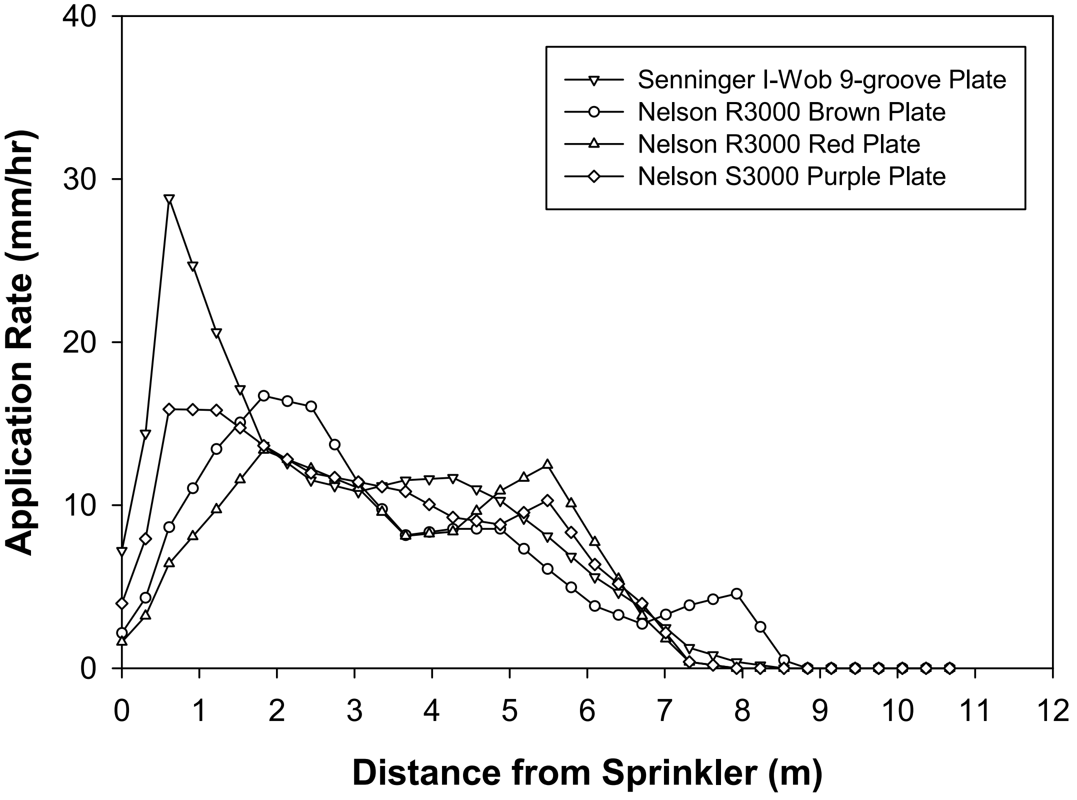

Figure 4. Radial application rate of low flow rate sprinklers used in this study.

Table 2. Computed kinetic energy per unit drop volume (KE_d) and applied kinetic energy per unit irrigation depth (KE_a) for each sprinkler used in study.

Sprinkler	KE_d J/L	KE_a J/m^2 mm
High Flow Rate		
Senninger I-Wob Standard 9-groove Plate	13.7	11.0
Nelson R3000 Brown Plate	13.5	9.7
Nelson R3000 Red Plate	13.3	12.2
Nelson S3000 Purple Plate	12.2	10.9
Nelson D3000 Flat Plate	8.6	11.8
Low Flow Rate		
Senninger I-Wob Standard 9-groove Plate	9.7	8.1
Nelson R3000 Brown Plate	12.1	9.4
Nelson R3000 Red Plate	10.1	9.0
Nelson S3000 Purple Plate	11.2	9.8

used to compare relative potential soil surface destructive effect of sprinklers (Kincaid, 1996; DeBoer, 2002).

Computed KE_d values for each of the four low flow rate sprinklers are also shown in table 2. Based on KE_d, the I-Wob sprinkler had the lowest kinetic energy and the R3000 brown plate sprinkler had the highest. The R3000 brown plate sprinkler had the highest KE_d because it had the largest drop size and largest wetted radius which is heavily weighted by equation 1. The S3000 sprinkler had the second highest KE_d because it had the second largest fraction of d_{98} to d_{100} drop sizes which travel the farthest from the sprinkler and are heavily weighted by equation 1.

Computed SP values for each of the five high flow rate sprinklers as a function of radial distance from the sprinkler are shown in figure 5. The D3000 sprinkler had the greatest peak SP value of all the sprinklers; approximately five times that of the other sprinklers. This outcome was not expected given the D3000 sprinkler had the smallest drop sizes of all the five sprinklers. This outcome demonstrates that despite the relatively small drop sizes of the D3000 sprinkler, kinetic energy is transferred to the soil surface at a relatively high rate due to the relatively small wetted radius of the sprinkler. The S3000 sprinkler has the second highest peak specific power due to the relative large drop size (fig. 1) and high peak application rate at a radial distance of 6.3 m (fig. 3). If peak specific power is a primary factor in soil surface seal formation and sheet erosion, the D3000 and S3000 sprinklers would not be sprinklers of choice. This outcome is contrary to conventional practice of recommending spray and spinner type sprinklers for soils susceptible to surface sealing. Thompson and James (1985) and Mohammed and Kohl (1987) found that as specific power increased, water infiltrated prior to ponding decreased, indicating that peak specific power maybe a primary factor in soil surface seal formation.

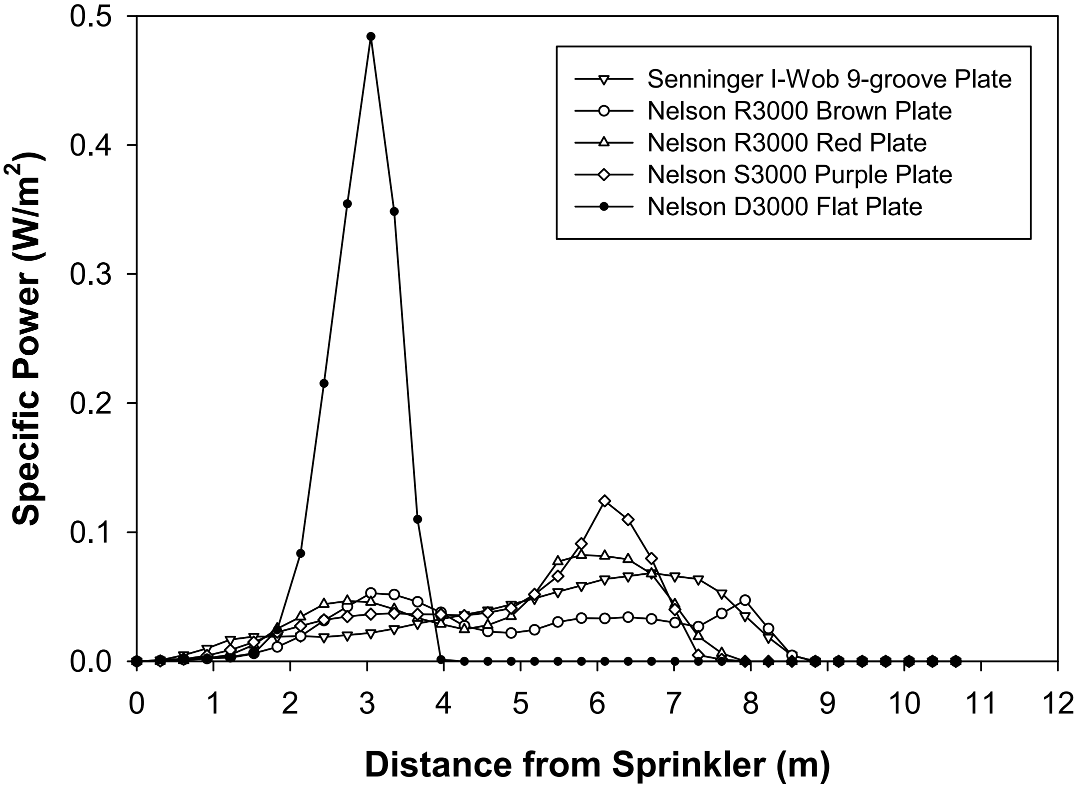

Figure 5. Radial specific power application pattern for high flow rate sprinklers used in study.

Computed SP values for each of the four low flow rate sprinklers as a function of radial distance from the sprinkler are shown in figure 6. The S3000 and R3000 red plate sprinklers have the highest and nearly identical peak specific power. This nearly equal peak specific power 5.6 m from the sprinkler is a result of the S3000 sprinkler having larger drops (fig. 2) and a lower application rate at 5.6 m from the sprinkler (fig. 4) and the R3000 red plate sprinkler having smaller drops and higher application rate at 5.6 m from the sprinkler which balance out in equation 2. The I-Wob sprinkler has the lowest peak specific power but only slightly lower than the R3000 brown plate sprinkler. The peak specific power for these two sprinklers coincides with the peak in application rates (fig. 4) demonstrating the effect application rate plays in determining specific power.

Composite water application rate distributions computed by the sprinkler overlap model are shown in figure 7 for each of the five high flow rate sprinklers used in the study. The composite water application rate distribution shown in figure 7 is an average rate between adjacent sprinklers spaced 2.5 m along the lateral. The horizontal axis in figure 7 is time rather than distance and represents time for the center pivot sprinkler lateral to pass over a fixed location. The area under each composite application rate distribution shown in figure 7 represents 25 mm of water application. Time average composite water application rates for the five sprinklers are given in table 3. The R3000

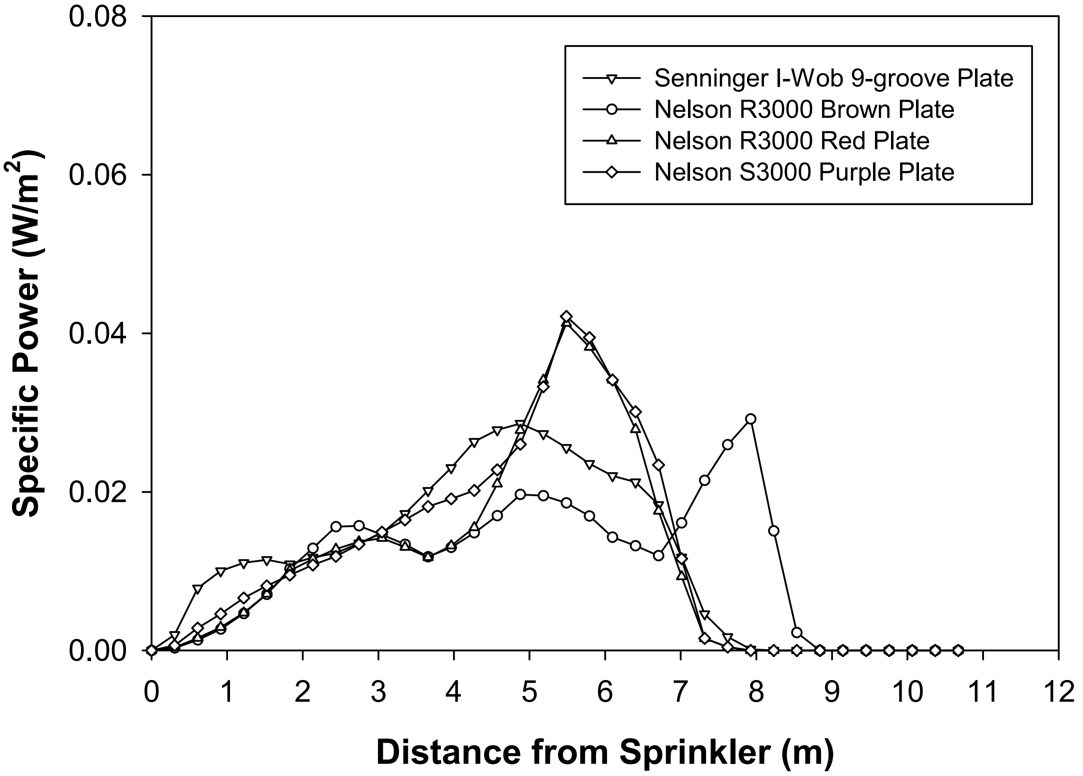

Figure 6. Radial specific power application pattern for low flow rate sprinklers used in study.

brown plate sprinkler had the lowest average composite water application rate and the D3000 sprinkler had the greatest. The average composite water application rate of each sprinkler is inversely related to sprinkler wetted radius since the flow rates of the sprinklers (based on manufacturer's published data) were nearly equal and sprinkler spacing along the lateral was equal.

Time average composite water application rates for the four low flow rate sprinklers are also given in table 3. The application rates are very similar since the flow rates of the sprinklers were nearly equal and sprinkler spacing along the lateral was equal. The R3000 brown plate sprinkler had the lowest application rate since it had the largest wetted radius of the four sprinklers.

Composite specific power distributions computed by the sprinkler overlap model using 2.5 m sprinkler spacing are shown in figure 8 for each of the five high flow rate sprinklers used in the study. The composite specific power shown in figure 8 is average specific power between adjacent sprinklers along the lateral. The horizontal axis in figure 8 is time and equivalent to that of figure 7 for each sprinkler. The area under each composite specific power distribution represents the total kinetic energy applied per unit area (J/m^2) for an irrigation application depth of 25 mm. The total kinetic energy applied by each sprinkler with 25 mm of water application is included in the legend of

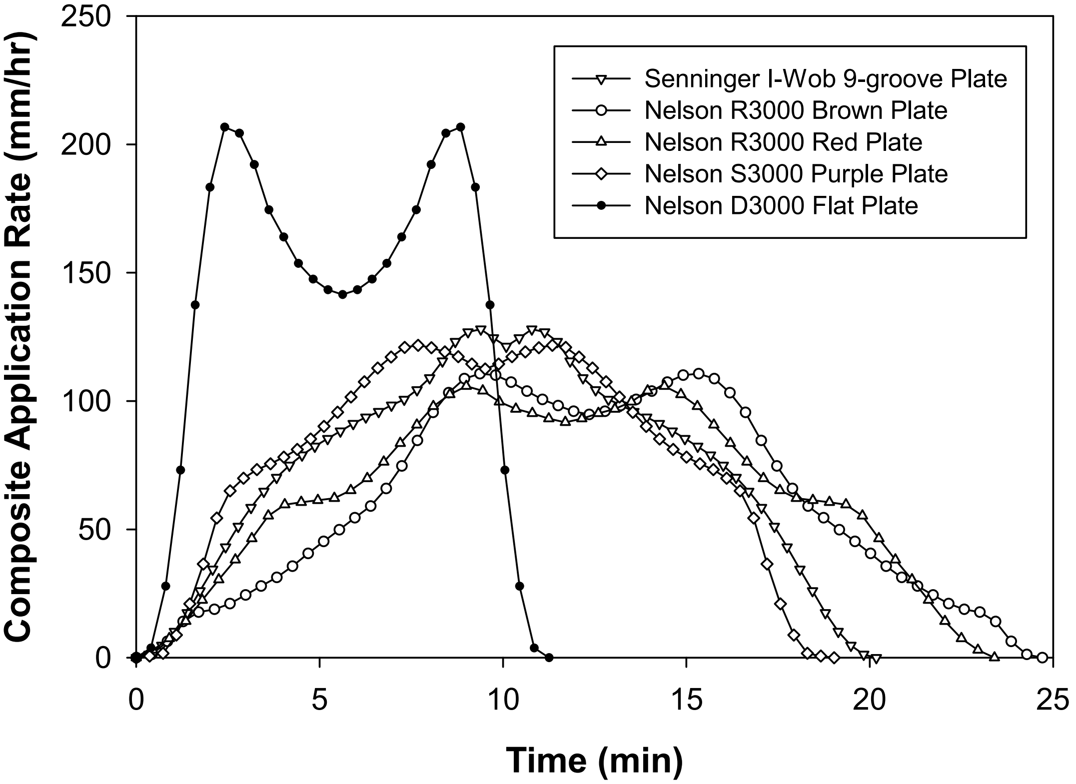

Figure 7. Composite application rate profile perpendicular to sprinkler lateral for each of the five high flow rate sprinklers used in the study. Sprinkler spacing along the lateral was 2.5 m. Time duration of each application rate pattern represents the time required for the irrigation system to apply an irrigation depth of 25 mm.

Table 3. Time averaged composite water application rate and time averaged composite specific power computed by sprinkler overlap program for each sprinkler used in study.

Sprinkler	Application Rate mm/hr	Specific Power W/m^2
High Flow Rate		
Senninger I-Wob Standard 9-groove Plate	73.3	0.224
Nelson R3000 Brown Plate	59.5	0.161
Nelson R3000 Red Plate	63.6	0.215
Nelson S3000 Purple Plate	77.2	0.234
Nelson D3000 Flat Plate	129.7	0.425
Low Flow Rate		
Senninger I-Wob Standard 9-groove Plate	36.2	0.085
Nelson R3000 Brown Plate	34.0	0.086
Nelson R3000 Red Plate	36.6	0.092
Nelson S3000 Purple Plate	36.8	0.100

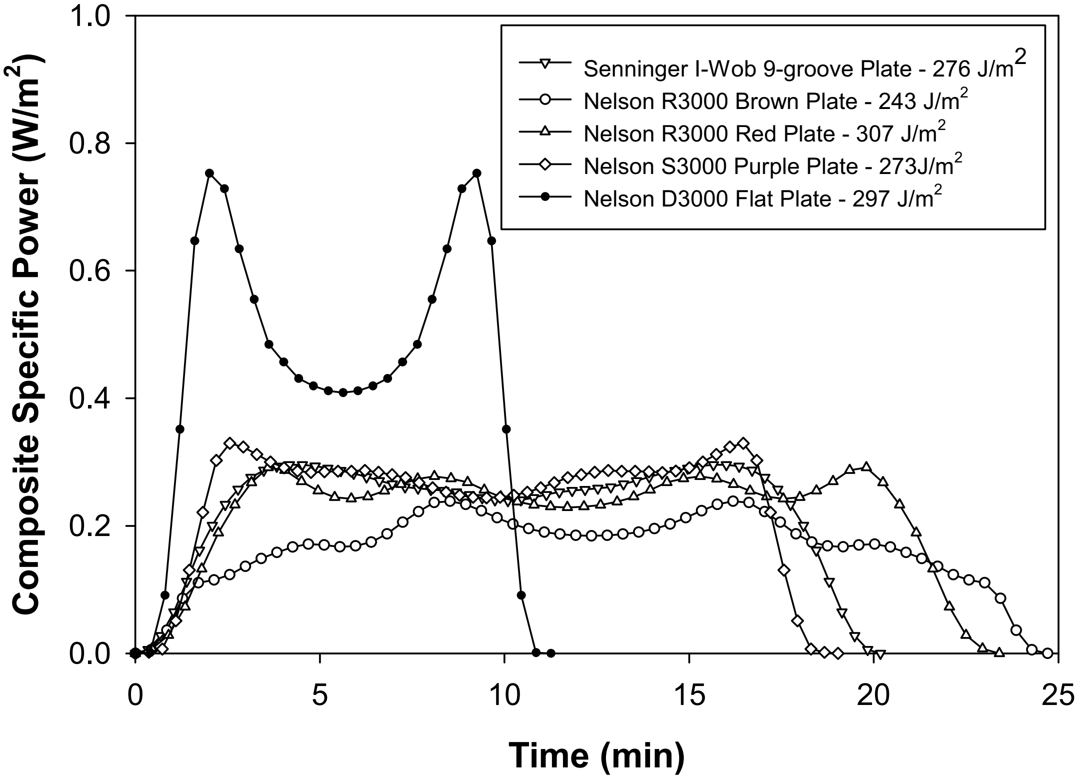

Figure 8. Composite specific power application profile perpendicular to sprinkler lateral for each of the five high flow rate sprinklers used in the study. Sprinkler spacing along the lateral was 2.5 m. Time duration of each application curve represents the time required for the irrigation system to apply an irrigation depth of 25 mm. The total kinetic energy transferred to a bare soil with an application depth of 25 mm is given in the legend for each sprinkler.

figure 8 for reference. Total kinetic energy per unit depth of water application, KE_a (J/m^2 mm) is shown in table 2 for all sprinklers used in the study. Total kinetic energy per unit depth of water application in units of J/m^2 mm is used because it is a more intuitive unit of measure than J/L but is numerically equivalent to kinetic energy per unit volume applied (J/L) (1 mm of water over 1 m^2 equals 1 L).

The relative ranking of all the sprinklers used in the study based on KE_d and KE_a (table 2) from highest to lowest is given in table 4. Spearman's rank correlation coefficient between KE_d and KE_a is 0.333 and not significant ($p = 0.38$) meaning that KE_d is not an indicator of actual kinetic applied by the center pivot irrigation sprinklers, even though it is currently used to indicate kinetic energy applied by a sprinkler. The relative ranking of the high flow rate sprinklers based on KE_a shows that the R3000 red plate sprinkler had the greatest kinetic energy applied and the R3000 brown plate sprinkler had the lowest kinetic energy applied. It was unexpected these two sprinklers that are hydraulically very similar (only different plate design) would apply the highest and lowest kinetic energy of the five high flow rate sprinklers used in the study. The R3000 red plate sprinkler did not have the largest d_{20} through d_{98} drop sizes but yet had the highest kinetic energy applied of the five high flow rate sprinklers. Another unexpected outcome was that the D3000 sprinkler with the smallest drop sizes would apply the second highest kinetic energy of the five high flow rate sprinklers. This outcome is contrary to conventional thought that center pivot sprinklers with small drop sizes transfer the least kinetic energy to the bare soil surface. This conventional thought follows from characterization of sprinkler kinetic energy based on equation 1 and relatively small drop sizes and wetted radius of the D3000 sprinkler.

Table 4. Relative ranking of sprinklers based on kinetic energy per unit drop volume (KE_d), applied kinetic energy per unit irrigation depth (KE_a), time averaged composite specific, power kinetic energy parameters. Ranking is from highest to lowest parameter value with 1 being the highest.

Sprinkler	KE_d	KE_a	Specific Power
<u>High Flow Rate</u>			
Senninger I-Wob Standard 9-groove Plate	1	3	3
Nelson R3000 Brown Plate	2	6	5
Nelson R3000 Red Plate	3	1	4
Nelson S3000 Purple Plate	4	4	2
Nelson D3000 Flat Plate	9	2	1
<u>Low Flow Rate</u>			
Senninger I-Wob Standard 9-groove Plate	8	9	9
Nelson R3000 Brown Plate	5	7	8
Nelson R3000 Red Plate	7	8	7
Nelson S3000 Purple Plate	6	5	6

Time averaged composite specific power for all the sprinklers used in this study are given in table 3. The relationship between average composite water application rate and average composite specific power for the five sprinklers is shown in figure 9. There is good linear relationship between the two average composite values with an $R^2 = 0.99$. This relationship was expected given that specific power is linearly related to sprinkler application rate (equation 2). The significance of the relationship shown in figure 9 is that efforts by center pivot sprinkler manufacturers to develop sprinklers with greater wetted radius to reduce composite water application rates has also reduced specific power applied. The relationship also shows that some relatively large drops from center pivot sprinklers that are needed to increase wetted radius and reduce composite application rate do not necessarily result in greater transfer of kinetic energy to the soil. Average composite specific power is based on the sum of drop size classes and not just a single drop size, thus if there are few large droplets, overall kinetic energy applied will not be affected.

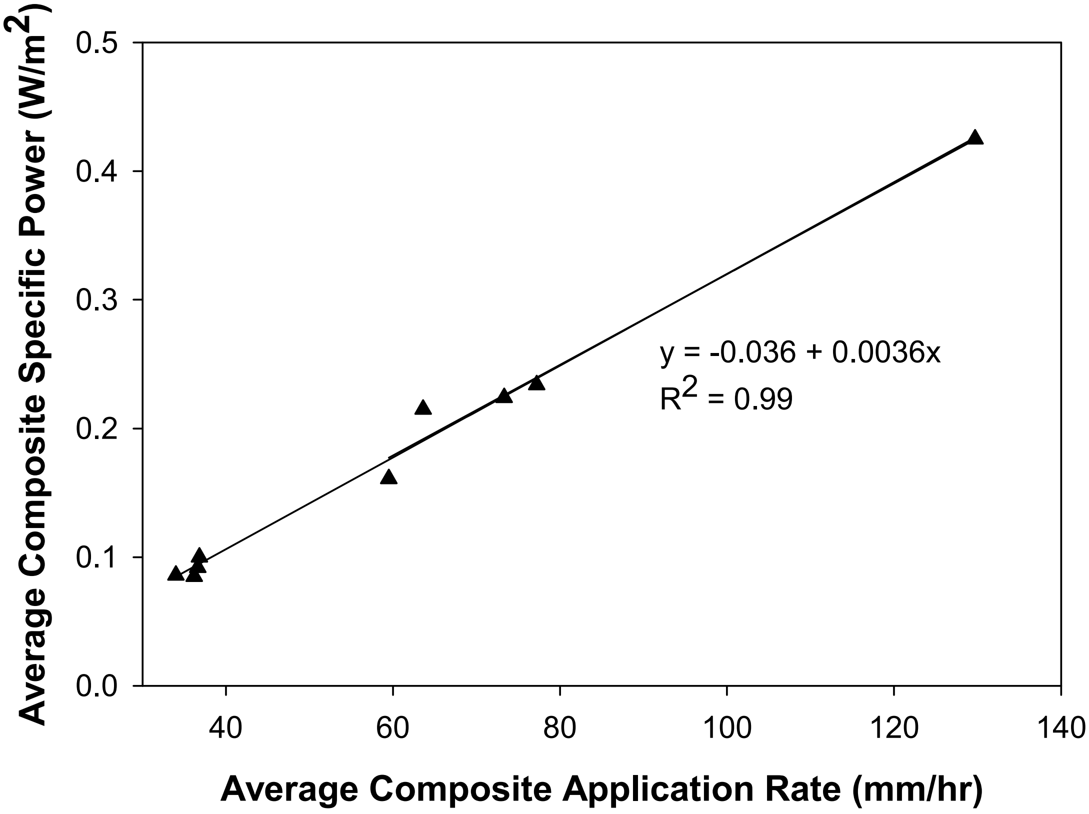

Figure 9. Relationship between average composite application rate and average composite specific power for the sprinklers used in the study.

The relative ranking of all the sprinklers used in the study based on time averaged composite specific power from highest to lowest is also given in table 4. Spearman's rank correlation coefficient between KE_a and time averaged composite specific power is 0.85 and significant ($p = 0.004$) meaning that KE_a and time averaged composite specific power are closely related as was expected since composite specific power is used to calculate kinetic energy applied. Correlations between average composite specific power and KE_a and runoff and soil erosion from sprinkler irrigation need to be investigated to determine which parameter best represents the effect sprinkler drops have on soil surface sealing and soil particle detachment and transport.

Conclusions

Area weighted kinetic energy per unit drop volume has traditionally been used in the literature to characterize kinetic energy transferred to a bare soil by sprinkler irrigation. Sprinkler specific power defined as the rate at which kinetic energy is transferred to the bare soil surface was used to calculate kinetic energy transferred to the soil by center pivot irrigation sprinklers. Kinetic energy transferred to the soil by five common center pivot sprinklers for a specific flow rates and lateral spacing was calculated based on measured drop size and velocity. The results demonstrated that area weighted kinetic energy per unit drop volume used to characterize sprinkler kinetic energy is not an indictor of kinetic energy applied to the soil under center pivot irrigation. Sprinklers with the smallest drop sizes do not necessarily transfer the least kinetic energy per unit depth of water applied. Conversely, sprinklers with the largest drop sizes do not necessarily transfer the greatest kinetic energy to the soil. Conventional thought that sprinkler drop size alone determines kinetic energy transferred to the soil is incorrect.

Acknowledgements

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Evaluation of pressure regulators from center pivot nozzle packages

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Abstract: *Performance evaluations of center pivot nozzle packages for uniformity have been conducted as part of the Mobile Irrigation Lab program for a number of years. These evaluations were performed using a catch can system. Later the evaluation expanded to spot checking pressure and flow for in-canopy nozzle packages that could not be tested with catch cans. However, the latter procedure did not measure the pressure drop across the pressure regulator and approximately 80 per cent of Kansas center pivot irrigation systems are pressure regulated. This study tested pressure regulator performance of regulators from existing center pivot nozzle packages.*

Keywords: Center pivot irrigation, pressure regulators

Introduction

Center pivot irrigation systems are the dominant irrigation system type in use within Kansas (Rogers et. al., 2007). Irrigation is also the dominant use of water supplies for the state, but in many areas of the state, water supplies are diminishing. However, irrigated agriculture makes significant contributions to the economy so improving irrigation water utility has long term benefits to the region. The Mobile Irrigation Lab (MIL) project previously developed a procedure to performance evaluate center pivot nozzle packages for uniformity (Rogers et. al., 2002). Later, the performance evaluation was expanded to include an evaluation procedure for in-canopy (low to the ground) nozzle packages (Rogers et. al., 2005), although, the performance evaluations did not focus on individual components. Approximately 80 percent of the nozzle packages were equipped with pressure regulators (Rogers et. al., 2007); however, the pressure drop across the regulator was not measured in the previous performance evaluation procedure. By observation, pressure regulator failure has appeared to be either excessive leaking at the regulator or clogging with no water passing, but otherwise the regulators were assumed to be functioning. In this study, pressure regulators from existing systems were collected and laboratory tested for performance.

Procedures

Two sets of 10 pressure regulators each were initially intended to be removed from various systems in southwest Kansas. Older nozzle packages were selected. The samples were normally collected from the third and last span of the system. In one case, all the pressure regulators from the system were evaluated. The regulators were subsequently brought to the hydraulics laboratory at the Department of BAE, Kansas State University. Each regulator was tested at two input pressures (20 and 30 psi) and three nozzles sizes appropriate to the flow rating of the pressure regulator.

Results and Discussion

Three hundred and nine pressure regulators were collected and tested. Only one regulator was recorded as failed. In this case, excessive leakage through the regulator body occurred, which was a part of the GFS3 test. The average results of this collection are based on the averages of the remaining 9 in the collection sample. In another case, a regulator had no flow passing through the regulator when it was initially installed on the test stand. It was removed, at which time debris was noted in the intake side which was then removed by tapping the regulator on a hard surface. This dislodged the debris, so the regulator was re-installed and tested.

An example of a pressure regulator performance chart is shown in figure 2. For the design output pressure or pressure rating, the downstream or output pressure will be slightly less than line (input) pressure due to friction losses through the regulator. Once the internal friction loss is overcome, the device will begin to output the approximate design rating. This value will generally be slightly elevated with increasing input pressure. The amount of flow through a pressure regulator will also affect the output pressure, with decreasing output pressure with increasing flow.

A summary of the results are in Table 1, where the average output pressure of the collected set are shown as well as the highest and lowest reading from the test set. The size of the nozzle is also noted in the table. Pressure regulators were collected from 8 different systems. On two systems only the outer span regulators were collected and on one system the S3 span had different pressure rated (6 psi) regulators than the LS span (10 psi); making 14 data sets. Based on figure 2 discussion, it would be expected that as nozzle size (higher flow) increased, the average output pressure would decrease. This was the case in 9 of the 14 sets for the 20 psi test. RKS3, RKLS, GFS3, MGLS, and RBLS did not follow the pattern of decreasing output pressure with increasing flow. At 30 psi, 8 of 14 followed the expected pattern with the same sets above and also GFLS breaking pattern. When comparing test results between 20 and 30 psi pressure tests, only RKS3, RKLS and TLLS did not have higher output pressure at 30 psi input pressure as compared to 20 psi, which would be different than the expected result. Overall, performance of the regulators seemed very good.

Figures 3 and 4 show the results of Test SFGF S3 and LS which are 6 psi rated regulators and, as noted previously, follow the expected pattern of performance. For example at 20 psi input pressure, the average S3 output pressure changes from 6.25 to 5.73 to 5.53 psi for the respective nozzle sizes. Figure 3 shows individual data points to indicate the range of values. Most test values are relatively close, although in the 20 psi LS test, one regulator had a test value of nearly 8 psi, which is an outlier as compared to the others. Figure 4 shows a different data presentation. In this figure, S3 and LS test results were averaged into a combined set. Note that flow through the nozzle has more impact on the output pressure than does the input pressure.

Figures 5 and 6 show the results of Test UB S3 and LS which are 10 psi rated pressure regulators. The S3 and LS models are the same but the former is a low flow model while the latter is a high flow model. As noted previously, they follow the expected pattern of performance. For example at 20 psi input pressure, the average S3 output pressure changes from 10.25 to 9.74 to 9.20 psi for the respective nozzle sizes. Figure 5 shows individual data points to indicate the range of values. Most test values are relatively close, although in the 30 psi LS test, the range of data points was larger than the other ranges. Figure 6 shows the data presented by nozzle size and the results show the decreasing output pressure with increasing nozzle size. The output pressures for the 20 and 30 psi input pressures were not as tight as in the SFGF example but still similar; with the average 20 psi LS test was slightly lower than the other average values

Figures 7 and 8 show the test results from 169 pressure regulators. These regulators were collected from one center pivot irrigation system in position order and tested at the two pressure and three flow rates as described previously. The most remarkable feature of either figure 7 or 8 is that the variability of results of the first thirty regulators as compared to the rest of the regulators from the position. At higher flows (figure 7), the regulators performed better, although still at higher output pressure as compared to higher numbers of position. The regulators also performed better at 30 psi (figure 8) than at 20 psi. No notable differences in appearance of the regulators during collection or during test installation were noted. S3 regulators as discussed previously would have been downstream of the variable area noted in this full system analysis.

Conclusion

Pressure regulators collected from a variety of center pivot systems located in SW Kansas were laboratory tested. Older nozzle packages were targeted. Although additional analysis of the data is planned, it appears the regulators performed well under the variety of conditions experienced in the region. One full system analysis was completed. Regulator performance in the inner part of this system was more variable than the outer part of the system, however no conclusions should be drawn from a single test.

Acknowledgements

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Table 1: Average, highest, and lowest Output Pressure of various pressure regulators for two input pressures and three flow rates.

Pressure Regulator ID	**Nozzle Size**	**Ave Output Pressure PSI**	**High Pressure PSI**	**Low Pressure PSI**	**Ave Output Pressure PSI**	**High Pressure PSI**	**Low Pressure PSI**
		Upstream Test Pressure = 20 psi			Upstream Test Pressure = 30 psi		
RKS3	15	10.21	11	9.5	9.86	10.9	8.4
10 psi	20	9.63	10.4	9.1	9.68	10.7	9.2
	24	10.26	11.6	9.4	10.47	12	9.1
RKLS	15	10.34	11.1	9.8	10.13	10.7	9.6
10 psi	20	9.93	10.5	9.6	9.78	10.7	8.4
	24	10.45	11.7	9.7	10.76	11.2	10.3
GFS3	15	5.28	6.3	4.2	5.73	6.70	4.60
6 psi	20	5.6	7.9	4.2	5.67	7.30	3.70
	24	5.47	8.50	4.20	5.51	7.50	3.60
GFLS	15	5.73	7.6	5.2	5.83	7.1	5.1
6 psi	20	5.73	7.2	4.9	5.97	7.2	4.7
	24	5.65	7.8	4.6	5.89	7.4	4.8

Pressure Regulator ID	**Nozzle Size**	**Ave Output Pressure PSI**	**High Pressure PSI**	**Low Pressure PSI**	**Ave Output Pressure PSI**	**High Pressure PSI**	**Low Pressure PSI**
MGLS	7	8.91	11.1	7.1	10.09	12.5	6.2
10 psi	12	7.84	11.1	4.6	7.84	10	5
	15	8.33	10.4	4.8	7.98	11.3	6.5
RBLS	7	5.79	7.5	5	6.16	7.1	5
6 psi	12	4.77	6.7	3.6	4.77	6.9	4.1
	15	4.92	6.3	4.2	5.32	6.3	3.7
SFGFS3	7	6.25	6.6	6	6.54	7	6.1
6 psi	12	5.73	6.1	5.2	5.98	6.3	5.4
	15	5.53	5.9	4.8	5.6	6.1	5.1
SFGFLS	7	6.51	7.9	6	6.6	7	6.2
6 psi	12	6.13	6.7	5.6	6.05	6.5	5.8
	15	5.79	6.3	5.3	5.52	5.9	5.2
UBS3	7	10.25	11.1	8.9	10.43	11.5	9.8
10 psi	12	9.74	10.5	9.2	9.86	10.7	9.2
	15	9.2	10.1	8.1	9.02	9.7	8.1
UBLS	15	9.7	11	7.7	10.32	12	8
10 psi	20	8.59	9.8	7.5	9.42	10.5	7.8
	24	8.55	9.7	7.3	8.64	9.2	7.7
TLS3	7	10.85	11.5	10.3	11.05	11.5	10.5
10 psi	12	10.24	10.6	9.6	10.39	10.7	10
	15	9.72	10.3	8.7	10.09	10.6	9.6
TLLS	15	6.51	7.6	5.2	6.34	7.1	5.8
6 psi	20	6.09	7.5	5.4	5.91	6.7	4.7
	24	5.88	8.2	4.7	5.54	6.6	4.7
ALS3	7	10.68	11.1	10.2	10.91	11.5	10.1
10 psi	12	10.21	10.5	9.9	10.12	10.6	8.6
	15	9.97	10.5	9.5	9.97	10.3	9.6
ALLS	7	10.48	11.1	9.9	10.6	11.3	9.9
10 psi	12	9.97	10.5	9.6	10.19	11	9.3
	15	9.7	10.1	8.8	9.66	10.1	8

Figure 1. Picture of Pressure Regulator Test Stand, including manifold, pressure regulator, pressure shunt, water meter, pressure shunt and flow nozzle.

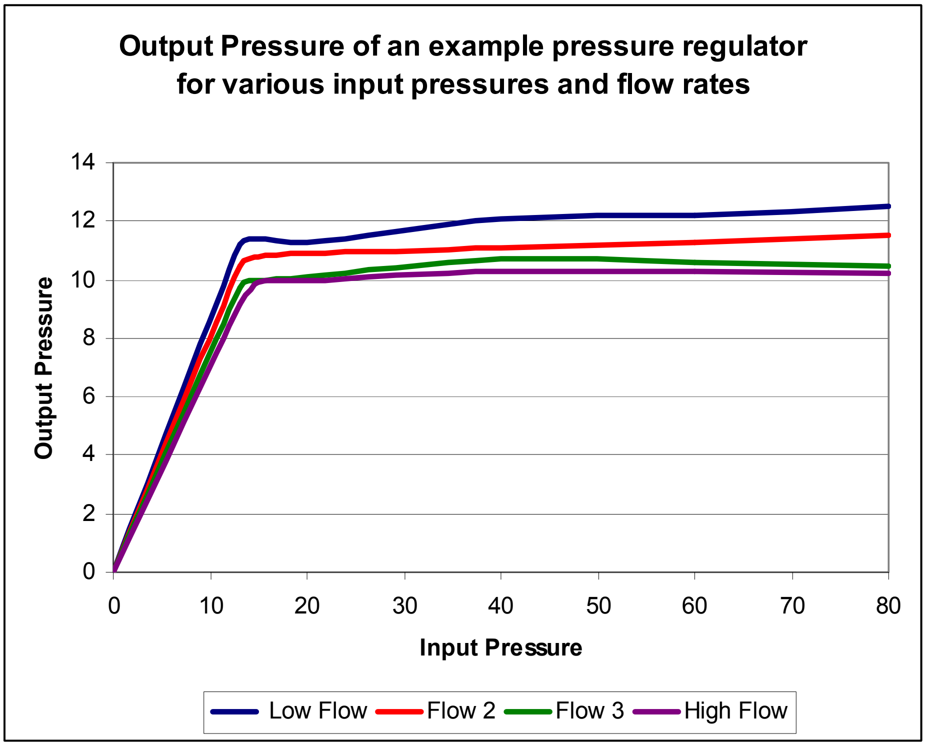

Figure 2. Example of Output Pressure verses Input Pressure for a Pressure Regulator.

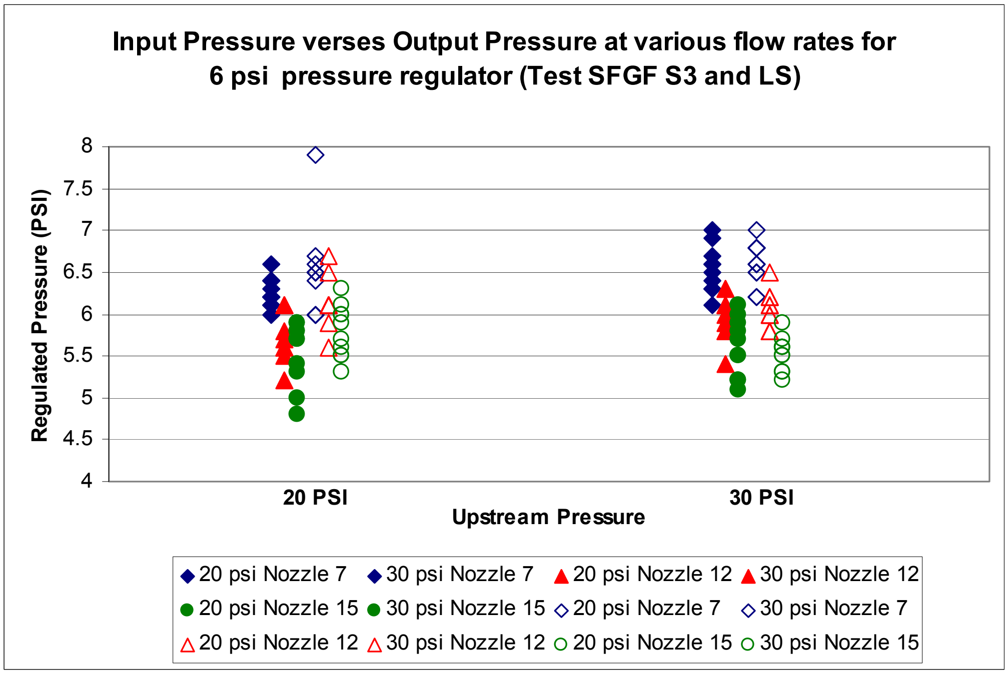

Figure 3. Input pressure verses output pressure at various flow rates for 10 6 psi pressure regulators for Tests SFGF S3 and LS.

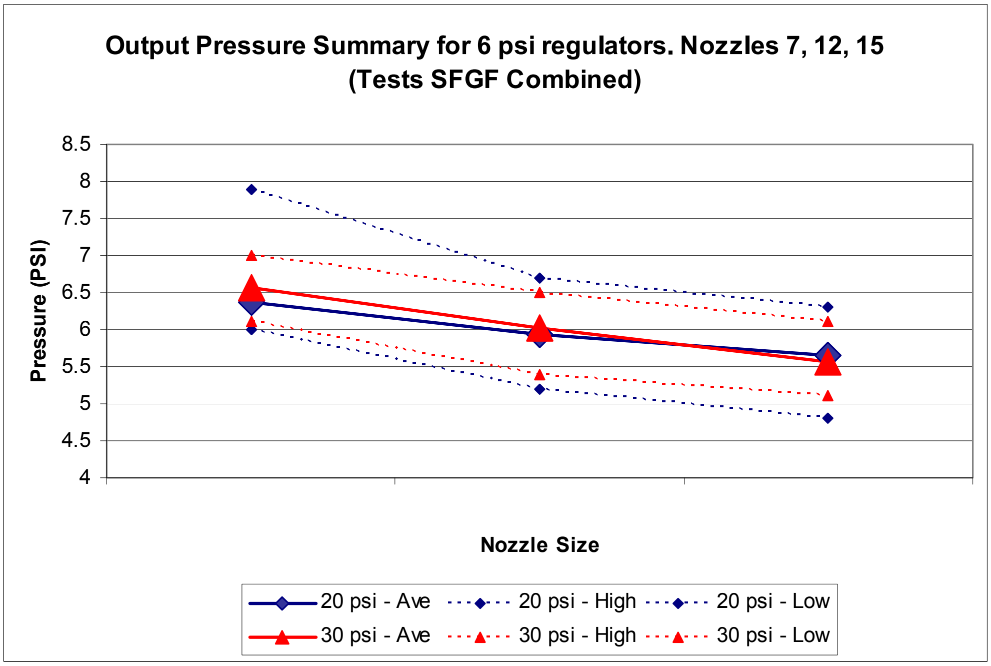

Figure 4. Average, high and low output pressures for 6 psi pressure regulators for Test SFGF S3 and LS.

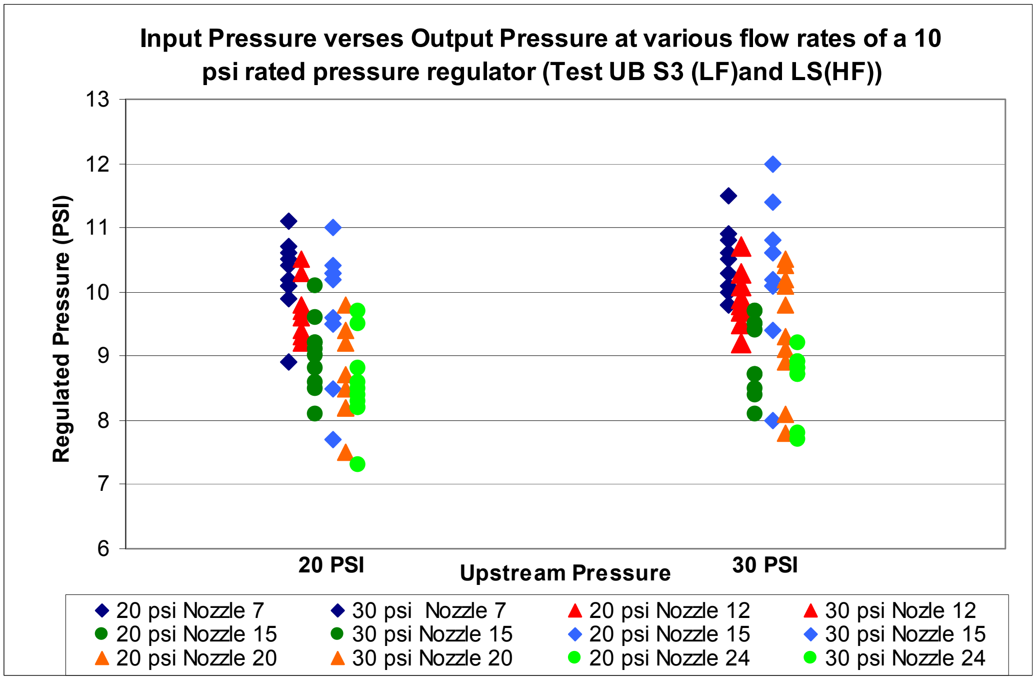

Figure 5. Input pressure verses output pressure at various flow rates for 10 psi pressure regulators for Tests UB S3 and LS.

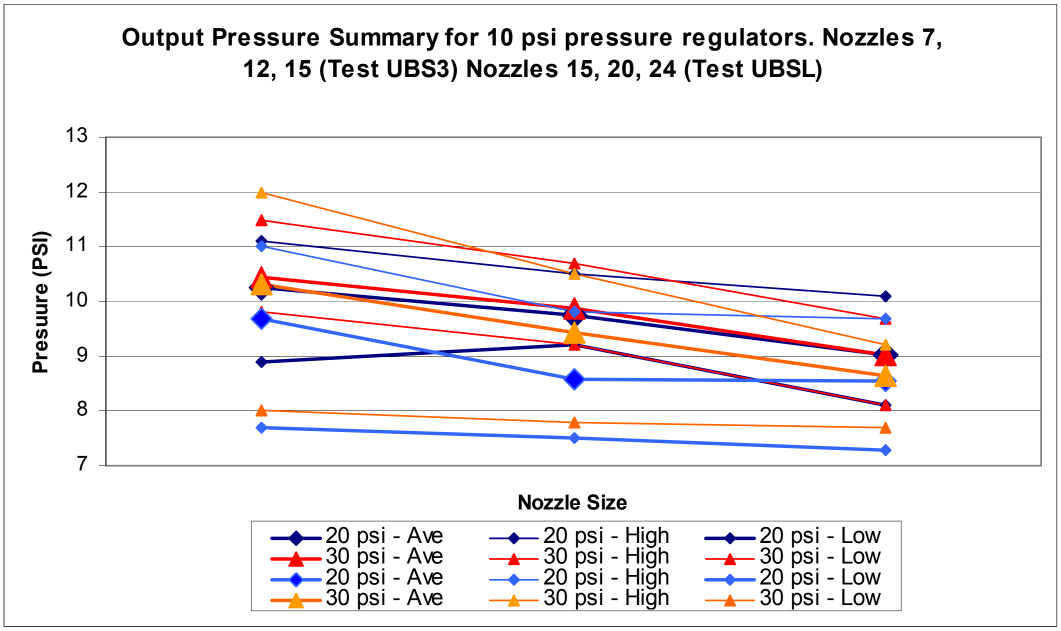

Figure 6. Average, high and low output pressures for 10 psi pressure regulators for Tests UB S3 and LS.

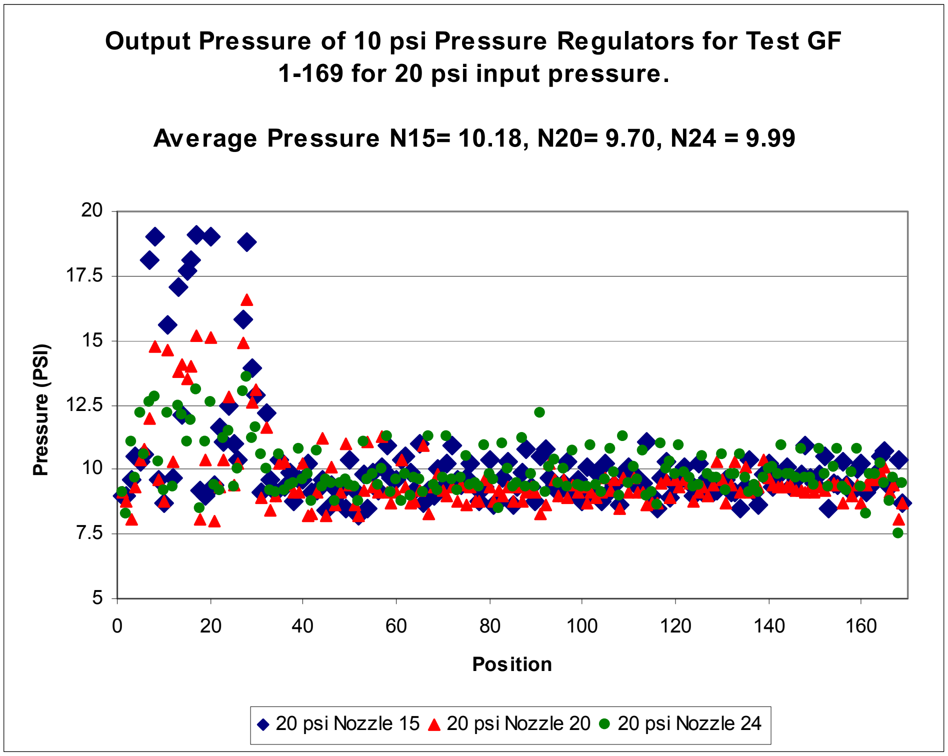

Figure 7. Output pressure of 169 pressure regulators tested at three nozzle sizes. Tests GF 1-169.

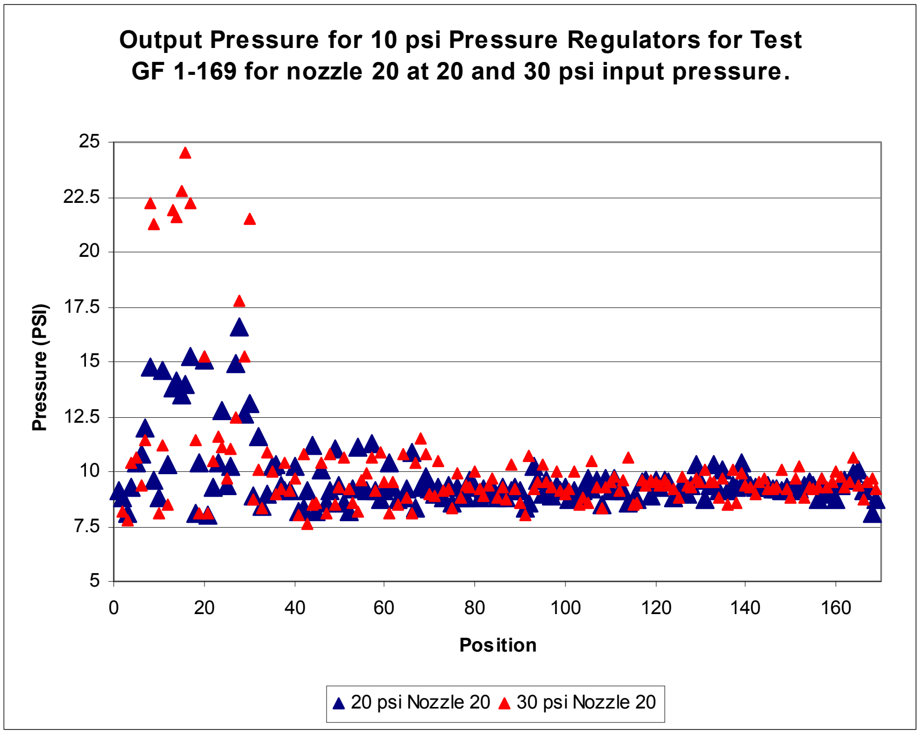

Figure 8. Output pressure of 169 pressure regulators tested at 20 and 30 psi input pressure. Tests GF 1-169.

APPLICATION OF GPS FOR PRECISION MECHANIZED IRRIGATION

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Summary

The development of control technology in precision mechanized irrigation has led to the application of GPS technology. We will illustrate the current status of GPS products from OEMs to third-party vendors and how their products apply to the mechanized irrigation industry. Information on product categories, products available, market acceptance, and costs compared to other options will be presented. Conclusively, we will focus on general information on the use of GPS, issues surrounding the use of GPS for precision irrigation, current applications, and future needs.

Introduction

GPS (Global Positioning System) was created and realized by the American Department of Defense (DOD), and was originally based on and operated with 24 satellites (21 required satellites and 3 replacement satellites). Today, approximately 30 active satellites orbit the earth from a distance of 20,200 km. From either the earth's atmosphere or low orbit, GPS satellites transmit signals which find the exact location of a GPS receiver; the receiver must be on the surface of the earth to acquire the GPS coordinates. GPS is currently being used in aviation, nautical navigation, and determining position on land. Furthermore, it is used in land surveying and other applications where the determination of an exact position is required. GPS is a free service that can be used by any person in possession of a GPS receiver; the only requirement is an unobstructed view of the satellites (ie: view of the sky) (kowoma.de, 2009).

Agricultural applications use GPS technology for equipment guidance; the equipment uses lightbar-guided and automated steering systems that help maintain precise swath-to-swath widths. Guidance systems are packaged with a display module that issues audible tones or lights as directional indicators for the operator's use. The operator monitors the lightbar to maintain the desired distance from one swath to the next. Automated steering systems integrate GPS guidance capabilities with the vehicle steering system.

GPS is also used with yield monitoring systems; the sensor is typically located at the top of the clean grain elevator. As the grain is transported into the grain tank, it strikes the GPS sensor and the amount of force applied to the sensor represents the recorded yield. The data is displayed on a monitor located in the combine cab and stored on a computer card that is transferred to an office computer for analysis (Nowatzki et al., 2001).

Another use for GPS in agricultural applications is field mapping in which it is used to locate and map specific field regions, such as areas that include high weed, disease, and pest infestations. Objects such as rocks and poorly drained regions can be recorded as landmarks for future reference. GPS is used to locate and map soil sampling locations, allowing growers to develop contour maps that show fertility variations throughout fields.

GPS has also been commonly used in agriculture for precision crop input applications. The technology is used to vary crop inputs throughout a field based on GIS maps or real-time sensing of crop conditions. Variable rate technology requires a GPS receiver, a computer controller, and a regulated drive mechanism mounted on the applicator. Crop input equipment, such as planters or chemical applicators, can be equipped to vary one or several products simultaneously (Kowatski et al., 2004). As GPS technology has been used in agriculture for several years, it is only logical that it should also be applied to mechanized irrigation.

With center pivots, control technology has been used for more than thirty years to stop the machine, reverse it automatically, and turn endguns on and off. These controls were originally based on electro mechanical switches stationed at either the last regular drive unit or at the pivot point. The function of these switches depended on their physical placement; it was often difficult to estimate how the pivot would behave, particularly when turning endguns on and off. Depending on certain circumstances, the endguns could turn on or off fifty feet or more from where the operator intended.

In the early 1990s, new position methods were developed by the center pivot manufacturers to provide position information to computerized control panels. These included, but were not limited to, resolvers and encoders. The position information was displayed on the panel, enabling the operator to determine settings that controlled endguns and stopping of the pivot. The computerized control panel then made the positioning decisions instead of trying to rely on mechanical switches. With the advent of computerized control panels, the door opened for multiple changes around the field, such as the control of six pie-shaped sectors or more, multiple settings on a single endgun, and control of a second endgun. These innovations moved mechanized irrigation into the realm of precision irrigation. If setup properly, these control panels were reasonably close to duplicating what the operator wanted; but, like the aforementioned mechanical switches, they were still using a positioning estimate at the pivot point, a large drawback. At this time, a decent solution for linear machine positioning did not exist.

In the past, the most successful guidance solution for center pivot corner arms depended on following a signal from a buried wire. Successful guidance for linears had three choices – following a furrow near the cart, following an above-ground cable (also near the cart), or following a signal from a buried wire (similar to the center pivot with a corner arm), which was usually placed near the middle of the linear machine. It was found that each of these guidance solutions have limitations due to the high risk of damage from farm operations and/or lightning.

Discussion

Mechanized irrigation manufacturers have been working on GPS applications since early 2000 (Segal & Chapman, 2000); the first commercial packages utilizing GPS for precision irrigation control arrived on the market a few years later (Reinke, personal communication, 2005). The early GPS applications were first focused on center pivots and secondly on linear machines in order to eliminate the need for cables and/or any other type of land-based guidance, such as furrow.

Work rapidly expanded to use GPS in providing position information to a center pivot as an alternative to electro mechanical devices reporting position at the pivot point. The GPS receiver is placed on the last regular drive unit and is controlled either by sending information to the computerized control panel or by sending the information directly to another control device. Market suppliers quickly entered the field, such Farmscan, which soon began to utilize GPS information to control banks of sprinklers based on a pre-determined prescription map (Farmscan, 2009).

Current applications of GPS with mechanized irrigation include reporting position for center pivots and linear machines, and guidance of linears and center pivots with corner arms.

Center pivots that utilize GPS technology on the last regular drive unit can replace previously used mechanical switches, resolvers, and encoders, which estimate position information from the pivot point. As the GPS receiver is stationed at the last regular drive unit, the technology provides more accurate information on the position rather than estimating the position of the last regular drive unit from the pivot point. Estimating from the pivot point has the potential for errors, unless the pivot alignment is maintained in an extremely straight position. The more spans on the center pivot, the more the risk for error due to nonalignment. Depending on the center pivot manufacturer, the grower may configure and adjust endguns or pivot stops using the GPS information found either at the computerized control panel or at the end of the center pivot with a PDA or laptop through Bluetooth technology. Third-party suppliers of GPS-based units operate independently from the control panel, providing information via the internet (Kim et al., 2006). Depending on the supplier, the GPS data can be used by the control device to program the on and off cycles for one or two endguns, stop, reverse, and change the speed of the center pivot, or, depending on the sprinkler hardware, turn on or off banks of sprinklers.

GPS technology is also being used for linear applications to control endguns and the machine's operation, which includes stopping, reversing, and changing speed. When utilized with linears, the GPS data is processed in a specially designed control panel, such as the Valley AutoPilot Linear.

On both the center pivot and linear GPS position, accuracies of +/- 3 meters is typically recorded with single-band GPS receivers and WAAS (Wide Area Augmentation System) correction signal.

Guidance for linear machines and center pivots with a corner arm is different from positioning in that the desired accuracy must be much higher in order to maintain correct tracking of the linear or corner (Barker, 2005). Generally, the accuracy is typically +/- 3 cm. To achieve this accuracy, the addition of a reference base station is required.

The marketplace has rapidly embraced the use of GPS technology in agricultural equipment, such as tractors, combines, and sprayers. GPS has literally become a part of the farming life. The acceptance of GPS for mechanized irrigation has begun to develop and flourish, and farmers expect GPS technology to be utilized with irrigation. Growers who currently use GPS for positioning linear machines and center pivots are pleased with the performance and the ease of operation. For instance, one farmer recently stated that his operators used to complain when the air conditioning went out of the tractor cabs, but now the first thing they complain about is when the GPS is malfunctioning (R. Pollard, personal communication, 2009).

Still today, some equipment manufacturers offer control panels without GPS to provide a traditional technology choice to their customers. The cost of GPS for center pivot or linear positioning varies with the type of package that best suits the customer's needs. Costs can be three to six times the price of an encoder or resolver type position sensor; however, the improved accuracies shown and recorded outweigh the high price tag.

GPS guidance for linear machines has good reception and acceptance by growers, the only drawback being the perceived cost. Customers using linear GPS guidance have experienced much improved performance and accuracies; this is because a linear machine always tries to maintain itself perpendicular to whatever guidance is being used, and the machine will continually steer itself to accomplish this. Each of the traditional types of linear guidance – furrow, above-ground cable, and below-ground cable – is difficult to install and/or maintain perfectly straight. As more steering is needed to keep alignment straight using traditional guidance solutions, there is more potential for non-uniform watering and delays moving down the field. Customers who have switched to GPS guidance have observed significantly less steering and more consistently completed field passes, which inevitably lead to better watering patterns and more dependable operation of the linear. The cost of GPS guidance varies greatly when compared to below-ground cable guidance, as in some cases, due to installation costs, the GPS guidance may actually be less expensive. Another major benefit of GPS guidance is it cannot be damaged due to lightning; in some areas of the United States, below-ground guidance cannot be used at all due to constant occurrences of sky to ground lightning.

Conclusion

Farmers expect GPS to become available for all of their equipment, including center pivot and linear irrigation machines. GPS has become a commonality for determining the current position of the last regular drive unit of a center pivot or a linear cart. OEM and third-party companies currently provide GPS options that determine position information. Using GPS to guide a center pivot corner arm and linear machines has been slower to gain acceptance due to the initial investment and limited data on reductions in operating costs and/or other associated benefits. Reliability and durability have proven to be very good and few issues surround the use of GPS for precision irrigation in the United States. Internationally, positioning offers some challenges due to the lack of a correction signal, such as the WAAS in the United States. Some areas do have DGPS (Differential Global Positioning System) correction, which improves the performance of single channel receivers. If correction is not available and improved position accuracy is desired, the only option is to use a dual channel receiver, which often costs five to eight times the cost of a single channel receiver.

Potential future changes in GPS technology include offering choices for tracking accuracy. It may also become possible to considerably reduce the initial investment if an operator will accept more variability in their wheel tracks.

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Using Wireless Networking and Remote Sensor Monitoring in Pivot Irrigation

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Abstract. As the automation of both private and corporate farms is embraced, the use of sophisticated pivot irrigation systems and smart agriculture practices is readily being adopted. Many new telemetry technologies are available today. It is common to have 100 percent communication to all farm pivot locations and see data throughput from pivot sites of 19.2 kbps up to 115.2 kbps.

The latest telemetry trend is “wireless instrumentation” or the ability to control or monitor analog and digital signals without the constraints of wire. These signals may be used to communicate to and from the pivot to the farm to check moisture and temperature sensors, chemical soil samples, wind speed for the best time to water, the actual pivot location and pump power usage. This capability, together with Internet access, allows the entire pivot system to be viewed anytime via a smart telephone. The farm can remotely operate the pivot system, report and view status changes, and see the remote sensors’ status. Until recently, all these field devices had to be hard-wired or use expensive cellular or satellite hardware. Now they can be done wirelessly utilizing spread spectrum 900MHz or 2.4GHz radios that have input and output control functions built right in. Some licensed VHF or UHF radio systems also offer IO options.

This paper reviews the advantages of using non-fee-based wireless networking and remote monitoring to more affordably, effectively track and report on pivot irrigation farms. It offers examples with pros and cons between traditional and newer approaches.

Kewords. Pivot irrigation, wireless networking, remote monitoring, spread spectrum, instrumentation.

Introduction and Background

Figure 1 - AmWest, Inc. installing pivot control box.

As the automation of both private and corporate farms is embraced, we see the use of sophisticated pivot irrigation systems and smart agriculture practices due to new technologies (see Figure 1). The human imagination continues to create new ways to use this technology and push those technology providers for more powerful tools. Ten to 15 years ago, even the most advanced automated pivot systems seldom used telemetry, and, if they did, the data throughput was extremely slow and seldom provided coverage to all the pivot irrigation sites. Some of the wireless technology also was expensive. Therefore, the telemetry technology was difficult to use effectively because only some sites could be remotely monitored or where farms were paying by the data byte or monthly usage fees to the technology provider.

With many new telemetry technologies available today, it is common to have 100 percent communication to all farm pivot locations and see data throughput from pivot sites of 19.2 kbps up to 115.2 kbps. Additionally, high speed backbone telemetry is available with both serial and Ethernet connectivity with speeds close to a megabit per second range. With the use of IP wireless devices, MPEG4 IP Ethernet cameras can be added to the system for remote viewing of the pivot system and to check on the field crop or farm conditions. In addition, hybrid wireless systems can be utilized where needed to combine different wireless technologies over large geographic areas or remote locations. This can include both cellular, satellite and microwave products that can be deployed for remote areas, or if a higher speed backhaul of data is required.

Figure 2 - Automated pivot irrigation SCADA system software by Reinke Irrigation

New radio products keep shrinking in size - but are getting smarter and most have both serial and Ethernet data interface options. Hybrid systems that use a mix of technologies is common as well, and can help save costs by using one technology that has monthly costs or fees and piggy-backing on to that network with a license-free system that can collect all the data from the local pivot irrigation sites back to that location. The use of GPS tracking devices is quite common to help with the location of the trailing end sprinkler on the pivot line and this information can be displayed on a computer screen or a PDA phone.

SCADA definition – Supervisory Control and Data Acquisition

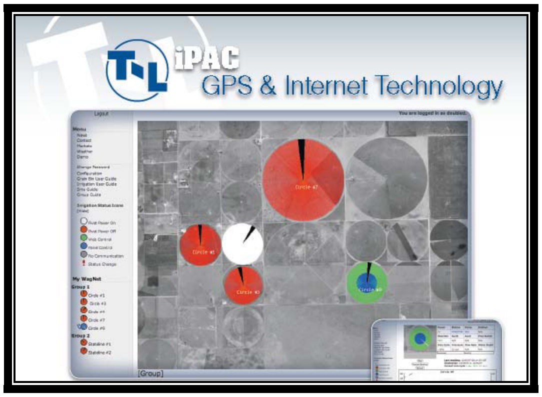

Figure 3: T-L Irrigation iPAC Control system

Figure 4: Lindsay Irrigation Field NET Software

The latest telemetry trend is "wireless instrumentation" or being able to control and/or monitor analog and digital signals without the constraints of wire. These signals may be used to communicate to and from the pivot to the farm to check moisture and temperature sensors, chemical soil samples, wind speed for the best time to water, the actual pivot location and pump power usage that can be viewed anytime. The capability with Web Internet access allows the entire pivot system to be viewed via a smart telephone or the user can look at a Website anywhere to have access to all the data and view the pivot irrigation system remotely. With this technology, the user of the farm can remotely operate the pivot system, report and view status changes, and see the remote sensors' status. Until recently, all of these field devices that had to be hard-wired, or use expensive cellular or satellite communication hardware, now can be done wirelessly and without any cost to the user using unlicensed spectrum with “spread spectrum 900MHz radios.” These radio products also can have input and output control functions built right in or can integrate into a remote terminal unit (RTU) or some other type of control device. One way they can send this information from the sensors to the host is using standard Modbus protocol and assigning Modbus registers to the field input devices.

Several pivot irrigation companies offer some type of wireless communication service that might include cellular, satellite, unlicensed or licensed radios or a combination of two technologies, depending on the farm location. The use of these wireless devices allows farm managers to view the operating status of the irrigation system, how much water is being used, the power consumption, and weather and soil conditions. Web-based programs allow access to this information from anywhere in the world as long as users have Internet access and the information can be displayed on PDA type cellular phones.

Some of the management tools that have been in the market place for a while include OnTrac from Rienke Irrigation, iPAC from T-L Irrigation (see Figure 3), Remote Tracker from Valley Irrigation, Field Net from Lindsay Corporation (see Figure 4) and Control Master from Pierce Irrigation (see Figure 5), to name a few. Some use their own software packages or web interfaces and others use off-the-shelf SCADA software, like Wonderware, Citect or Intellusion that can be customized specifically for each user and is fairly inexpensive. The use of field sensors and weather monitors is another way to optimize and ensure that the correct amount of fertilizer, water and time of watering is applied.

The use of wireless has created an influx of technology that has impacted the speed, size and variety of devices that can be embedded into the controllers, sensors and remote devices that have very small power requirements and can run off small lithium batteries or small DC power sources. The new wireless products have become smarter and have the capability to work in several different field environments. Along with all the new wireless products, there are several new antenna options available today that can help with difficult antenna mounting locations, constrained space, and variety of gain and antenna patterns.

Wireless devices with IO (input and output) capability are common, and analog and discrete information can be sent back and forth from the radio to the host or SCADA software. The most common way of doing this is using Modbus protocol and assigning Modbus register values to the input and output required. (see Modbus definition) These devices include pressure, temperature, flow sensors or valves that can be remotely turned on or off. Pump status and GPS coordinates can be carried back to the host computer and displayed with the SCADA software.

Figure 5 – Pierce Irrigation Control Master software and controller

History of the Modbus protocol

Some communication standards just emerge. Not because they are pushed by a large group of vendors or a special standards organization. These standards—like the *Modbus interface*—emerge because they are good, simple to implement and, therefore, are adapted by many manufacturers. Because of this, *Modbus* became the first widely accepted fieldbus standard.

Modbus established its roots in the late 1970's. In fact, it was 1979 when PLC manufacturer Modicon—now a brand of Schneider Electric's Telemecanique—published the Modbus communication interface for a multidrop network based on a master/client architecture. Communication between the Modbus nodes was achieved with messages. It was an open standard that described the messaging structure. The original Modbus interface ran on RS-232, but later Modbus implementations used RS-485 because it allowed longer distances, higher speeds and the possibility of a true multi-drop network. In a short time, hundreds of vendors implemented the Modbus messaging system in their devices and Modbus became the de facto standard for industrial communication networks.

The great thing about the Modbus standard is its flexibility, but, at the same time, it also is the ease of implementation and use of it. There are intelligent devices, like microcontrollers, PLCs, etc. that is able to communicate via Modbus, but many types of sensors that have standard analog or discrete outputs can send their data to host systems. While Modbus previously was used on wired serial communication lines, there also are extensions to the standard for wireless communications and TCP/IP networks.

Modbus Message Structure

The Modbus communication interface is built around messages. The format of these Modbus messages is independent of the type of physical interface used. The same messages used on *Modbus/TCP* are the same as on plain old RS232 over Ethernet. . This gives the Modbus interface definition a very long lifetime. The same protocol can be used regardless of the connection type. Because of this, Modbus allows users to easily upgrade the hardware structure of an industrial network without the need for large changes in the software. A device also can communicate with several Modbus nodes at once, even if they are connected with different interface types, without the need to use a different protocol for every connection.

Figure 6 -- AmWest, Inc. installing the Pivot Controller with 900MHz Radio

Center Pivot Innovators

Even before the first patent on center pivot technology ran out, **Valley Manufacturing** (later named **Valmont Industries**) had competitors. Lawsuits often followed, but the competition pushed innovation forward. Valmont is headquartered in Valley, Neb.

The Raincat. By 1959, an Australian company had modified the basic Valley approach and produced a center pivot system called the Grasslands. It featured many innovations that would become the standards for the industry in the future. The machine had electric motors to drive it (rather than water drives) and a truss system under each pipe span to bow and support the pipe (rather than overhead cables). A California pump manufacturer, Layne and Bowler, brought the system to America, put rubber tires on it and renamed it the Raincat. But California farmers didn't need center pivots as badly as farmers on the Plains. So, the company went through several ownership changes, eventually landing in Greeley, Colo. Raincat went out of business in the early 1980s.

Reinke. Richard Reinke was a Nebraska farmer's son who taught himself to be an engineer and draftsman. In 1954, he started Reinke Manufacturing in Deshler, Neb., and introduced his first center pivot system in 1966. To avoid infringing on Valley's patents, Reinke had to come up with new ideas, and he did. He was the first to make his electric drive systems reversible, so that a farmer could back the system up. He was the first to put his electric motors in the middle of each tower base and connect drive shafts to the gearboxes on each wheel. He was the first to patent the "bow-string" truss system under the pipe spans that most pivots use now. He was the first to use a electrical "collector ring" to transfer power from the pivot point down the spans so that a wire wouldn't wrap up as the pivot went around and have to be unwrapped after each revolution. In all, he patented more than 30 innovations for center pivot designs. Richard Reinke died in 2003 at the age of 80, but his company is still operating in Deshler. They've diversified into building trailers and chassis equipment for over-the-road trucks.

Lindsay. Lindsay Manufacturing is based in the small Nebraska town of the same name where Paul Zimmerer and his two sons set up shop in 1958. First, they made tow-line irrigation systems. Ten years later, they came out with their first center pivot system under the name "Zimmatic." Because the terrain around Lindsay was hilly, they introduced a "uni-knuckle" joint at each tower instead of the ball-joint that other builders used. This allowed the Zimmatic to move over very rough hills and valleys. They also used an external collector ring – instead of Reinke's internal ring – to transfer electrical power down the system. The company grew fast, and in 1974 the Zimmerers sold out to DeKalb AgResearch. But the family continued to operate the firm. Finally, in 1988 the company again went independent through an over-the-counter stock offering.

T-L Irrigation. Leroy Thom was a Hastings, Neb., area farmer who had tried his hand at everything from custom combining to irrigation engineering. In 1969, he and his two sons, Dave and Jim, decided they could improve on the other center pivot designs by using hydraulic motors on each tower. Hydraulics would enable their systems to move around the field at a constant rate rather than starting and stopping at set intervals. The company claims that their systems are more reliable, can be fixed by farmers who are used to hydraulic systems and apply water more evenly. Today, T-L Irrigation employs more than 250 people in Hastings.

Lockwood Corporation actually started in 1935 in Gering, Neb., to produce potato-farming equipment. In 1969, it decided to get into the irrigation business and bought a small Texas firm that was making the "Hydro-Cycle" pivot system. It moved the operation to Gering and completely redesigned the system. It became one of the five largest manufacturers of center pivot systems. In the late 1990s, the company went through ownership changes and is now known as Universal Irrigation Company, although the systems are still marketed under the Lockwood brand name.

AmWest, Inc. is located in Ft. Lupton, Co. For more than 25 years, AmWest has delivered full-service water equipment strategies, technology, installation, maintenance and expertise to its customers primarily through out the Rocky Mountain region, but also on a global scale (see

Other Innovators. Over the years, there have been more than 80 individuals or companies who have tried to make and sell center pivot systems. Some of the smaller companies were bought by the giants. For instance, when Valmont realized that farmers saw an advantage in the undertruss system to support the spans, they bought out a small company in Grant, Neb., that was building an undertruss system.

Other small companies started up, fought for market share for a while and migrated to other businesses.

Kroy. In York, Neb., a car dealer named Paul Geis had a small business making irrigation pipe and began making center pivot systems in 1968. He marketed the systems under the name of "Kroy" – York spelled backward. But his compressed air drive system didn't really catch on. Geis sold the center pivot business to a well driller in Sidney, Neb., who quit the business in the late 1970s. Geis continued to manufacture aluminum and PVC pipes and fittings for industry, construction and other irrigation methods.

Oasis. Just down the road from York in Henderson, well driller Gus Thieszen took his own chance in the center pivot business in the late 1960s. Thieszen brought out his "Oasis" model center pivot then, but the system never really caught on. He stopped manufacturing the system after only a few years. He was one of scores of Ag innovators who tested the market and had to fold up their enterprise.

Pivots Go Worldwide. Today, only six center pivot manufacturing companies remain, and the four largest – Valmont, Lindsay, Reinke, and T-L – are in Nebraska. Wade Rain and Pierce Irrigation are in Oregon. On this "Then & Now" page, today's center pivot market is outlined in www.livinghistoryfarm.org.

Also, Robert Daugherty remembers how the worldwide market for Valmont pivots just seemed to develop as news of the innovation spread around the agricultural community. The other manufacturers saw similar interest, but worldwide market challenged some of the smaller manufacturers.

Ref: http://www.livinghistoryfarm.org/farminginthe50s/water_05.html

Figure 7 and Figure 8 – AmWest, Inc. installing a control box with a 900 MHz Spread Spectrum Radio

Conclusion

The use of wireless products will continue to grow. With commercial farms trying to conserve water resources, manage power use, have access to the health of the pivot system and handle the crops that grow at anytime and anywhere - they will need more wireless technology. The bandwidth requirements will increase too, and other IP devices will be added and be more common place. New embedded products will help save costs and be part of the system instead of being an after thought. The use of different radio frequencies, field sensors, faster connection speeds and other wireless products will continue - software and other services will help the farm and farmer have all the information they need at their fingertips (see Figure 9 and Figure 10).

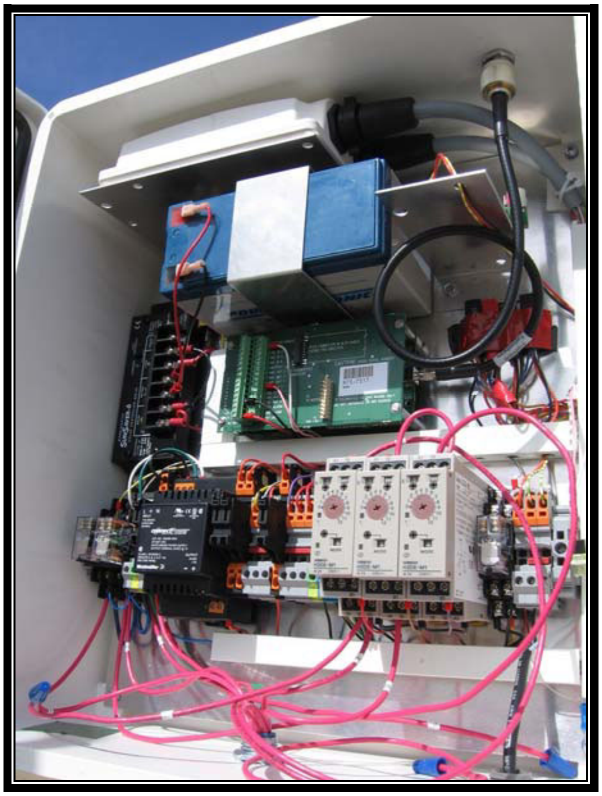

Figure 9 -- Master RTU/ Controller and 900MHz Radio that communicates to each pivot control box at the Farm.

Figure 10 --New variable frequency drive for the pivot irrigation water pump that will save energy costs and help prolong the Pump life.

Acknowledgements

I appreciated the opportunity I had to visit with all of the Pivot Manufacturers and for all the engineering, skills and hard work that it takes to manufacture Pivot Irrigations systems and many are installed all over the world. We have many arid places on earth that irrigation is the only way Farmers can grow crops and produce. I also want to express gratitude to AmWest Controls for the resources, pivot irrigation experience and actual field photo's. Finally, for Wessel's Living Farm in York, NE. I applaud their efforts, resources, farm information and the work they do for the preservation of rural farm life in America.

Wessels Living Farm
5520 South Lincoln Ave.
York, NE 68467 (Just south of Interstate 80 and US Highway 81)
It's open each Wednesday (excluding holidays) for tours, or by special appointment.

Founded in 1993, FreeWave Technologies manufactures the most reliable, high performing, lowest power consumption, spread spectrum and licensed radios for mission-critical data transmission. Through engineering excellence and a relentless commitment to best-in-class manufacturing, FreeWave customers enjoy superior radio up-time, range and the lowest cost of ownership available. Based in Boulder, Colorado, FreeWave designs and manufactures radios that are the leading choice for oil and gas, utility, military and numerous other industrial applications. Organizations that count on radio data communications for operational success – where failure and down-time are not an option – trust FreeWave for custom network design, system engineering and customer support that is unparalleled in the market. For more information visit the company's website at www.freewave.com.

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Solar Powered, Constant/Continuous Move Micro Center Pivot

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Abstract

The Solar Powered Pivot uses High Torque, 48 Volt, DC Motor(s) as prime means of moving the pivot in the field. The Pivot can be operated at any time with Deep Discharge batteries, charged by Photovoltaic Solar Panels. This allows pivots to run without the use of high-tension cables and electrical wires. The batteries & photovoltaic solar panels move with the pivot, eliminating the need for collector rings, thereby reducing electrical maintenance. This constant/continuous move pivot operates in a straight line, allows even distribution of water, and increases yield. Because all towers move continuously, multiple starts and stops are minimized, reducing stress on the structure, while increasing the life and reliability of the pivot. The constant/continuous move is facilitated by a Micro-controller unit, installed on each tower, is designed to calculate and control the synchronous speed of each tower. The micro-controller units are field-programmable. A slip timer design also senses the slippage of any pair of wheels, halting the pivot to reduce water waste and possible system damage. This control system is designed to sense the lag or lead of a particular tower and any deviation in the movement is corrected automatically. This concept is currently designed for a micro-pivot; however it can be adapted for use in larger diameter pivots.

Key Words: Center Pivot, Solar Power, Synchronous Speed, Slip Timer, Constant/Continuous move, Real Time Clock (RTC), Logic Controller, Standard Tower Controller, End Tower Controller, Yield.

Prologue:

Irrigation is the most important factor contributing to the process of harvesting any crop. Scientific progress has improved on the traditional means of irrigating croplands. Now, where abundant solar power is available, this renewable source of energy can be used to power irrigation systems.

Introduction:

Center pivot irrigation is popular and used extensively worldwide. The challenges encountered with most systems include:

1. The sprinkler spans move in a zigzag fashion and this motion prevents an even distribution of water. This adversely affects crop yield.
2. Power failure or cuts can also affect continuous operation of the pivot system.

Our Solar Powered Micro Pivot utilizes solar energy to power the pivot movement. This creates a substantial advantage to farms that have an abundance of hot, sunny weather.

Our system has been designed as a constant / continuous move system, thus avoiding the jerky, stop / go span motion, providing even water distribution. It reduces maintenance costs, and increases the life cycle of the pivot. Continuous motion reduces the wear and tear on motors that need to start from zero to full speed and back to zero. The controller allows for a narrow band of deviation in lateral / linear movement thus reducing the probability of misalignment. Our software-driven stall timer detects wheel-churning, shuts down the pump and halts the machine, preventing water waste and tire wear.

The Pivot:

Our pivot system has a center pivot point with a number of spans or towers, which revolve around the pivot point. The system can have from 3 to7 towers, each spanning a length between 90 to 130 feet, depending on the size and shape of the farm. Water is connected at the pivot point. When the structure is carrying water, and system is operating a coupler and rubber boot prevent water leakage. Each tower is built using a stable 'A' frame structure. It is operated with a 48 Volt-100 Watt, geared DC Motor, and driven by heavy duty gear boxes and tractor tires. The last tower, also called the end tower, moves at a maximum speed of 6 feet per minute, which can be reduced by 10% to increase the water discharge. Beyond the end tower is a cantilevered extension, which adds an additional 20 feet to the structure. A Logic Control box installed at the pivot point controls all machine operations.

Safety Features:

- Reverse Battery Connection
- Reverse PV Connection
- Over/Under Voltage cutoffs
- Overload protections
- Generally the machine works on a 60 Volt nominal DC supply, but can operate safely between 52 to 70 Volts
- LED indications for all above.

Logic Controller Features:

- Real Time Clock (RTC)
- Non Volatile (NV) RAM for 24X7X365 Real Time Operation,
- Battery backup saves data in the event of power failure.
- 20X4 Alphanumeric LCD Display indicates:
  - Machine status and diagnostic purposes.
- Operational parameters such as:
  - Starting Time
  - Run Hours or End Time
- Direction of Rotation (Clockwise, Counter Clockwise)
- End Limit Sensors detect boundary locations when pivot is not making 360 degree rotation and controls the Pivot operation.
- Real Time Clock tracks stop times.

Logic Controller Signal mode:

Power:	60 Volt DC Power being delivered to all towers
Pump:	Operates pump during Wet Mode
Speed:	Variable speed control from 10% to 100% by potentiometer Failsafe Current loop of 4-20 mA
Direction:	Signals all tower controllers to travel in pre-set direction
End Gun:	Pivot will water corners of square or rectangular fields. Can be programmed to remain in ON position for extra coverage if desired

The Logic Controller Receive mode:

Clockwise Start (CW):	Pivot starts in CW direction.
Counterclockwise Start (CCW):	Pivot starts in CCW direction.
Stop:	Stops pivot.
Misalignment:	Failsafe signal stops pivot if alignment off over 7.5^0
CW Limit Switch:	Receives this signal when Pivot reaches CW end of the farm.
CCW Limit Switch:	Receives this signal when Pivot reaches CCW end of the farm
Pressure Switch:	Stops pivot when low pressure is detected. Used during Wet Mode Operation only.
End Gun On:	Instructs controller to water corners. Used mainly for square and rectangular-shaped croplands.
Temperature Indicator:	Shuts off pivot if air temperatures fall below zero.

Machine operation modes:

Auto Restart	ON	Stops the pivot under Low voltage condition (< 52 Volts). Once power is restored, pivot resumes operation.
	OFF	Once machine has stopped, pivot must be restarted manually.
Auto Reverse	ON	System oscillates between two end limits.
	OFF	System travels to one end and stops.
Wet/Dry	WET	Machine starts pump, checks water pressure and continues to work. This feature is critical when pump stops due to power failures or loss of water.
	DRY	Mainly used during diagnostic testing mode and parking.
Misalignment		If any tower alignment is off by 7.5 degrees; machine & pump are shut off. System must be manually aligned before restarting.
Normal operation		Each tower of the machine moves in synchronous speed, moving the entire system in a straight line. Any tower that lags by more than 3.5 degrees, it will move at a higher speed and catch up. Alternately, if a tower advances by 3.5 degrees, it stops and brings it back into alignment. A slip timer tracks churning of wheels.
All above conditions are indicated by bright LEDs on the Main Panel at the pivot point.		

Standard Tower Controller:

This controller is common to all the other towers, except the last one. It is a micro controller based unit and works on 52 to 72 Volts. The synchronous speed of the tower is adjusted by settings of the Dual in Package (DIP) switches & depends on total number of towers and its position from the pivot point. Normally, all the towers move at synchronous speed to run the machine in a straight line. A specially designed integrated sensor detects position of particular tower with respect to the next tower. The sensing angle is generally 3-3.5 degrees, for synchronizing purposes. If it finds that a tower is lagging, the controller increases the speed. A tower that advances ahead of others is stopped to bring it back to synchronous speed. The continuous feedback loop makes the system stable, reliable and keeps it in synchronization. Synchronous speed makes the pivot to run continuously in a straight line around the pivot point.

End Tower Controller:

This is a Micro controller base unit & operates on 52 to 72 DC Volts, which drives the End Tower Motor. The speed feedback is used in the system to regulate the speed of the motor, under Power Supply and Load fluctuations. Speed is maintained constant, regardless of voltage variations between 50-72 volts and uphill and downhill slopes up to 25 degrees (tested at local installation). The constant speed governs the total movement and distributes water more evenly. The CW & CCW end limit switches and the End Gun are routed through this controller. The speed of the motor is governed by 4-20mA current loop set by Logic Controller.

Basic Features:

Power

1. System works on SOLAR energy, no external electrical power is required. Operation is not jeopardized due to power outages, power failures, or power maintenance and shortages.
2. Solar power charged storage batteries allow the machine to be operated any time, including nighttime.
3. No need to install underground or overhead high-tension wires or cables to the field.
4. If external electrical power is used, collector rings are required. Use of solar power, eliminates the need for collector rings.
5. Since irrigation must be used in sunny, hot and dry conditions, a solar power pivot provides an ideal application of this technology.

Conclusions:

Continuous Motion Pivot advantages:

- Avoids multiple starts and stops
- Reduces wear and tear and stress on all components
- Improved reliability and longer life-cycle
- Reduced wheel churn
- Improved water distribution, improves crop yield
- Stall Timer detects abnormal conditions and shuts down system
- DC motor improves stalling torque and increases the gradient of movement
- Spikes on power source are reduced

We have operated a three-tower system at the National Research Centre for Onion & Garlic, at Rajgurunagar, near Pune, Maharashtra, India, for last three (3) years. It is a 380-foot machine and was operated continuously for more than 20 hours with no solar charging required.

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Managing the Challenges of Subsurface Drip Irrigation

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Abstract. *This paper will discuss from a conceptual standpoint many of the challenges of subsurface drip irrigation (SDI). Topics will include soil water redistribution as affected by soil type and soil characteristics, nutrient availability, differential crop response, system installation concerns, and system maintenance issues. The paper and presentation will summarize material obtained by the author in preparing for a recent book chapter concerning SDI and will also show examples of the challenges as a tool to broaden their conceptual understanding. .*

Keywords. Emitter, microirrigation, irrigation design, SDI.

Introduction

Subsurface drip irrigation (SDI) is defined as the application of water below the soil surface by microirrigation emitters. The discharge rate of the emitters is usually less than 2 gal/h (ASAE S526.2, 2001). Some shallow subsurface systems (< 8 in depth) are retrieved and/or replaced annually and are very similar to surface drip irrigation. Many research reports refer to these systems as surface drip irrigation, and reserve the term SDI for systems intended for multiple-year use that are installed below tillage depth (Camp and Lamm, 2003). However, that is an arbitrary distinction based on usage rather than whether the system is installed below ground and the actual definition mentioned at the beginning of this paragraph is probably better overall. This discussion will concentrate on SDI systems with driplines deeper than 2 inches and this may help limit the discussion to SDI systems that have more similarity in design characteristics and operational properties.

SDI is suitable for a wide variety of horticultural and agronomic crops, and, in many respects is applicable to those crops presently under surface drip irrigation (DI). SDI has been a part of modern agricultural irrigation since the early 1960s. Investigations of both SDI and DI with citrus crops and potatoes were conducted by Sterling Davis, an irrigation engineer with the United States Salinity Laboratory, in 1959 (Davis, 1974; Hall, 1985). At about the same time in Israel, Blass (1964) was reporting early experiences with SDI. SDI performance was often plagued by problems such as emitter clogging (chemical precipitation, biological and physical factors, and root intrusion) and poor distribution uniformity. However, as improved plastic materials, manufacturing processes, and emitter designs became available, resurgence in SDI occurred, both in research activities and commercial operations. SDI has been used primarily for high-valued horticultural crops (fruits, vegetables, and ornamentals), tree crops (nuts and fruits), vineyards, and sugarcane. As system reliability and longevity improved, SDI has begun to be used with lower-valued agronomic crops (cotton, peanuts, and cereal crops). This is primarily because SDI system's longevity has increased to the point that investment costs can now be amortized over longer periods.

Although there are numerous advantages for SDI (Lamm, 2002; Lamm and Camp, 2007) there are also many unique challenges to successful use. The adaptation and adoption of SDI systems into diverse cropping systems are unpredictable and depend on the geographical region, soils and climate conditions, and, to a large extent, on how potential advantages are balanced against potential disadvantages. In addition, cultural differences, traditions, skills, and perceptions can have a large influence on whether SDI will be accepted. SDI requires concentrated and consistent management of both water and nutrients to assure adequate crop performance and is also less forgiving than other irrigation systems (Phene, 1996).

Adoption of SDI in a new region can be hampered by the lack of good information on design, management, maintenance, and crop performance, along with the lack of qualified equipment distributors and installers. A goal of this paper is to discuss some of the unique challenges of SDI as a means of broadening their conceptual understanding so that SDI adoption can be optimized in regions where it is appropriate. A broader conceptual understanding can help the novice SDI system end-users ask the right questions and can help researchers and extension specialists formulate new techniques and strategies to alleviate some of these challenges. Much of this paper summarizes material obtained by the author in preparing for a recent book chapter concerning SDI (Lamm and Camp, 2007). Topics will include the challenges associated with design and installation, soil types and characteristics, cultural practices, differential crop response, maintenance, system monitoring and operation.

Challenges with SDI System Design and Installation

Suitability and Site Selection

Although SDI is technically suitable for a vast number of crops in many diverse regions, it may not be the best irrigation system choice for specific situations. Water managers, system designers and producers should not automatically assume that SDI can be successfully adopted. Suitability and site considerations have been the subject of several recent publications that can aid in making appropriate decisions (Lamm et al., 2003; Dukes, et al.; 2005; Grabow et al., 2005; Burt and Styles, 2007; Lamm and Camp, 2007; Rogers and Lamm, 2009).

Subsurface drip irrigation systems may have a higher initial investment cost than the typical alternative irrigation system used in many regions. In many instances, the SDI system has no resale value or minimal salvage value. Lenders may require greater equity and more collateral before approving SDI system loans. Such large investments may not be warranted in areas with uncertain water and energy availability, particularly where crop yield and price outlook is poor. SDI systems typically have a shorter design life than alternative irrigation systems, which requires that the annualized depreciation costs must increase to provide for system replacement.

SDI is often a less-developed technology than other types of irrigation systems particularly in regions where growers have little exposure and experience with these systems. Often, turn-key systems are not readily available. In some regions, the lack of contractor capacity can result in less than optimal installation timing during wet periods. Design errors are more difficult to resolve because most of the SDI system is below ground. More components are typically needed for SDI than surface drip irrigation (DI) systems. Soil materials can possibly enter the driplines (soil ingestion) at system shutdown if a vacuum occurs. Air relief/vacuum breaker devices must be installed and be operating correctly to prevent this problem. As with any microirrigation system, zone size and length of run will be limited by system hydraulics. Compression of the dripline due to soil overburden can occur in some soils, causing adverse effects on flow. There are also many possible soil water redistribution issues that affect suitability. Many of the soil factors will be discussed in later sections of this paper. SDI systems are not typically well suited for Site Specific Variable Application (SSVA) because the zone size is to a great extent fixed at installation and may not spatially represent the location needing variable application very well.

Areas with variable or shallow soil overlaying rock may not be suitable for SDI because of shallow or restricted depth. Coarse sands and non-bridging soils may also be unsuitable for SDI. When using thin-walled driplines, the weight of the overburden may collapse or deform the dripline, which will reduce the flowrate. Undulating or rolling topography presents design challenges that may limit SDI suitability because of the added hazard of backsiphoning soil material into the dripline when the system shuts down. SDI installed on cracking and heavy clay soils may cause soil water distribution problems that may limit its use on the crops of the region. This can sometimes be avoided with alternative irrigation systems that apply water to the soil surface. In arid and semiarid regions, the limitations on SDI use for crop establishment and salt leaching are added suitability considerations. Crop establishment with SDI can also be a problem on coarse-textured soils or when short drought periods occur at planting in the more humid regions.

Cropping practices of a region may affect the perceived suitability of SDI. In regions where high-value horticultural, tree, and vine crops are grown, the grower may have an erroneous perception that SDI presents more economic risk than DI because of the lack of easily observed indicators of SDI system operation and performance. Although many of these negative perceptions can be overcome, growers may be unwilling to change their cultural practices or management (Phene, 1996). Adequate soil water for crop germination with SDI is important in semiarid and arid regions and in other regions prone to drought during crop establishment.

Certain crops may not develop properly under SDI in some soils and climates. For example peanuts may not peg properly into dry soil and some tree crops may benefit from a larger wetting pattern than SDI can provide in a typical system design. Root intrusion from some crops may limit SDI suitability while crop harvest problems might be an SDI concern for other crops. Some of these issues will be discussed in more detail in a later section of this paper concerning Challenges with Differential Crop Response.

Saline water application through SDI may result in adverse salt buildup at the edge of the wetted soil volume or above the dripline in the seed or transplant zone, which can hamper crop establishment and plant growth. Care must be taken in plant placement relative to the dripline position to avoid these high-salinity zones. Leaching of the salinity zone above the dripline is often necessary. In some regions, these difficulties in salinity management have reduced or prevented the adoption of SDI.

Physical Characteristics of SDI Systems, Driplines, and Emitters

Dripline depth

The choice of the appropriate dripline depth is affected by crop, soil, and climate characteristics, anticipated cultural practices, grower experiences and preferences, the water source, and prevalence of pests. Camp (1998) reported in an extensive review of SDI that the placement depth of driplines ranged from 1 to 28 inches. The depth was determined primarily by crop and soil characteristics. In most cases, dripline depth was probably optimized for the local site by using knowledge and experiences about the crop for the soils of the region.

SDI systems for lower-valued commodity crops (fiber, grains, and oilseeds) and perennial crops (trees and grapes) are usually set up exclusively for multiple-year use with driplines installed in the 12 to 20-inch depth range. Most of these crops have extensive root systems that function properly at these greater depths.

Soil hydraulic properties and the emitter discharge affect the amount of upward and downward water movement in the soil and thus are factors in the choice of dripline depth. When surface wetting by the SDI system is not needed for germination or for salinity management, deeper systems can reduce soil water evaporation and weed growth.

Deeper dripline placement will minimize soil water evaporation losses, but this must be balanced with the potential for increased percolation losses, while considering the crop root-zone depth and rooting intensity (Gilley and Allred, 1974; Thomas et al., 1974; Philip, 1991).

Surfacing is an SDI phenomenon in which excessive emitter discharge, coupled with insufficient soil water redistribution, creates or uses an existing preferential flow path to allow free water to reach the soil surface. Surfacing can sometimes be avoided with deeply-placed driplines (See section Challenges with Soil Types and Characteristics), but this is only an acceptable solution when the mismatch of emitter discharge and soil properties is small and the added soil depth provides a larger soil volume for water redistribution.

Soil layering or changes in texture and density within the soil profile affect the choice of dripline depth. Driplines should be installed within a coarse-textured surface soil overlaying fine-textured subsoil so that there is greater lateral movement perpendicular to the driplines. Conversely, when a fine-textured soil overlays a coarse-textured subsoil, the dripline should be installed within the fine-textured soil to prevent excessive deep percolation losses. An excellent discussion of how soil texture and density affect soil water redistribution is provided by Gardner (1979).

The dripline should be deep enough that the anticipated cultural practices can be accommodated without untimely delays, soil compaction, or damaging the SDI system. The grower's depth preference must be considered with respect to rooting characteristics of the crop and the soil's water redistribution properties. Some growers prefer that the soil surface be periodically wetted with SDI as an indicator of system performance, even though this promotes greater soil water evaporation losses and weed germination. Some growers in the Salinas and Santa Maria Valleys of California have abandoned SDI in favor of DI for broccoli, cauliflower, celery, and lettuce rather than contend with harvesting issues associated with buried driplines (Burt and Styles, 1999). Pests such as rodents and insects are often more troublesome at the shallow dripline depths.

Saline waters and biological effluents often impact the choice of a dripline depth. The application of saline water at shallow dripline depths may create a zone of high salinity near or at the soil surface that is detrimental to seedling and transplant growth and establishment. In arid areas where precipitation is insufficient, it may become necessary to leach this zone with sprinkler irrigation. Some growers have used tillage to scrape off or displace this salinity zone before each planting. The dripline depth for application of biological effluents is chosen so that the pathogen exposure paths at the soil surface are reduced, but with a depth that would not prevent normal biological decay.

The use of SDI in regions subjected to freezing and frozen soils adds an additional dripline depth consideration. Deeply placed SDI systems are less likely to freeze, but supporting system components (e.g., valves and filters) sometimes may freeze and limit operation (Converse, 2003). Snow cover can insulate and protect the SDI system from very cold air temperatures. SDI was durable enough to withstand winters in the U. S. Northern Great Plains when temperature at the 12-inch dripline depth was below freezing for 90 consecutive days in 1993-94 and the frost depth reached 36 inches (Steele et al., 1996).

Greater dripline depths can limit evaporation and decrease rainfall runoff, but may cause greater percolation of applied water or reduce beneficial transpiration in shallow-rooted crops. These conditions can reduce the effectiveness of applied water and thus application efficiency. The interactions between the soil water budget components with dripline depth are also closely affected by soil type and crop characteristics. The unsuccessful adoption of SDI in many regions is caused by the improper balancing of these interrelationships or by the lack of understanding of the need for the proper balance.

Dripline spacing

Crop row or bed spacing is usually set by cultural practices for a given crop in a given region and by planting and harvesting equipment specifications. As a general rule, SDI dripline spacing is a multiple of the crop row spacing, whereas emitter spacing is usually related to the plant spacing along the row. Providing the crop with equal or nearly equal opportunity to the applied water should be the goal of all SDI designs. This presents a conflicting set of constraints when crops with different row spacing are grown with SDI. Mismatched crop row/bed and dripline spacing may not only result in inadequate irrigation and salinity problems, but also in increased mechanical damage to the SDI system (Ayars et al., 1995). Adoption of similar row/bed spacing for crops on a farming enterprise may be advantageous, provided that the crops produce adequate yields under that spacing.

Dripline spacing is usually one dripline per row/bed or an alternate row/bed middle pattern with one dripline per bed or between two rows. SDI systems on some widely spaced tree crops may have multiple driplines between tree rows to wet a larger portion of the canopy floor. In a review of SDI, Camp (1998) reported dripline spacing from 0.8 to 16 ft, with narrow spacing used primarily for turfgrass and wide spacing often used for vegetable, tree, or vine crops on beds. The soil and crop rooting characteristics affect the required lateral spacing, but there is general agreement that the alternate row/bed dripline spacing (about 5 ft) is adequate for most of the deeper-rooted agronomic crops on medium- to heavy-textured soils. Wider dripline spacing may be suitable in soils with layering, allowing increased horizontal soil water redistribution above the soil layer, and in regions that are less dependent on irrigation for crop production. Closer dripline spacing has been suggested for high-valued crops on sandy soils (Phene and Sanders, 1976) and/or in arid areas to ensure adequate salinity management and consistent crop yield and quality (Devitt and Miller, 1988).

Emitter spacing and discharge

Emitter spacings ranging from 4 to 30 inches are readily available from the manufacturers, and other spacings can be made to meet a specific application. Increasing the emitter spacing can be used as a technique to allow larger emitter passageways less subject to clogging, to allow for economical use of emitters that are more expensive to manufacture, or to allow longer length of run or increased zone size by decreasing the dripline nominal flowrate per unit length. The rationale for increased emitter spacing must be weighed against the need to maintain adequate water distribution within the root zone. An excellent conceptual discussion of the need to consider the extent of crop rooting in irrigation design is presented by Seginer (1979). Although the effective uniformity of microirrigation experienced by the crop is high, the actual detailed uniformity within the soil may be quite low. It should be noted that using the widest possible emitter spacing consistent with good water redistribution can cause significant problems when emitters become clogged. However under full irrigation, emitter spacings as great as 4 ft have not proven detrimental to field corn production on the deep silt loam soils of semi-arid Kansas (Arbat et al., 2009).

Wide ranges of emitter discharge are available from the various dripline manufacturers. The evapotranspiration (ETc) needs of the crop generally have little influence on the choice of emitter discharge because most emitter discharges at typical emitter and dripline spacings have application rates well in excess of peak reference ETc. Some designers prefer emitters with greater discharge because they are less subject to clogging and allow more flexibility in scheduling irrigation. When emitters with greater flowrates are chosen, the length of run may need to be reduced to maintain good uniformity and to allow for adequate flushing within the maximum allowable operating pressure. In addition, the zone size may need to be reduced to keep the total system flowrate within the constraints of the water supply system. Decreasing the length of run or the zone area increases the cost of both installation and operation. The choice of emitter discharge must take into account the soil hydraulic properties to avoid backpressure on the emitters and surfacing of water.

Dripline length and diameter

A guiding principle in microirrigation design is to obtain and maintain good water application uniformity along the length of the driplines. Dripline and emitter characteristics and hydraulic properties, the system operating pressure, and the land slope are the major governing factors controlling the hydraulic design. When soil compaction is likely to occur, dripline lengths may need to be reduced to maintain the initial system uniformity. These factors determine the acceptable dripline lengths for the SDI system with respect to the field size and shape and grower preferences. Longer driplines may result in a less expensive system to install and operate, which is of great importance to those growers using SDI on lower-valued crops. Longer dripline length is less important to growers of higher-valued crops, however, and may limit the grower when applying precise water and chemical applications to remediate site-specific crop and soil problems or to elicit a site-specific crop response.

Longer driplines with higher uniformity can be designed by increasing the dripline diameter while holding the emitter discharge constant (Fig. 1). This design technique is popular for larger SDI systems used on the lower-valued commodity crops (fiber, grains and oilseeds) because it can help to reduce installation costs through fewer pipelines, controls, and trenches. This design technique is not without its concerns, however, because larger dripline diameters increase the propagation time of applied chemicals, and dripline flushing flowrates can become quite large.

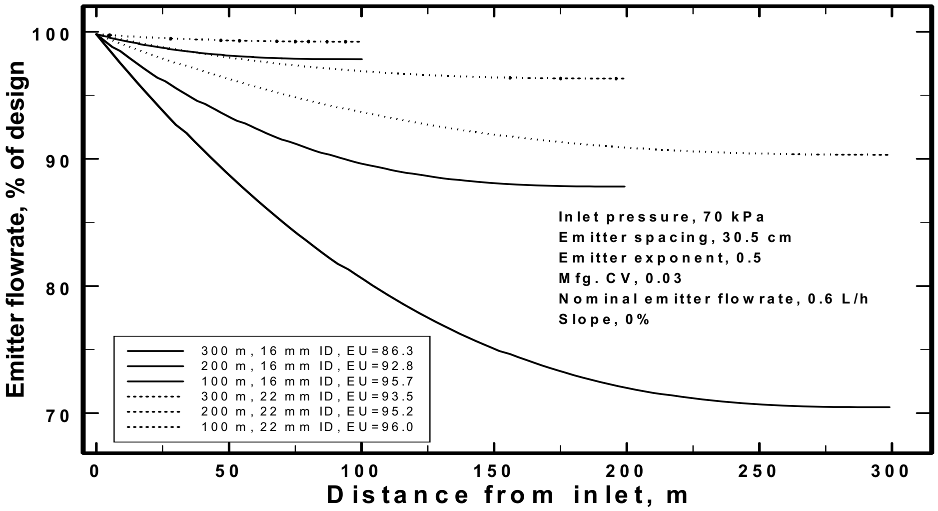

Figure 1. Calculated emitter discharge and emission uniformity (EU) as affected by dripline length and inside diameter. Results for hypothetical dripline calculated with software from Roberts Irrigation Products[1] (2003).

Limited research has been conducted in evaluating the injection of gases into the soil profile with SDI. Gases might be injected for fumigation, aeration, fertilization, or even to modify soil temperature. Compressible gas and gaseous water mixture flow and distribution through the SDI system are much different than standard water flow and distribution (e.g., changes in flow characteristics due to viscosity and friction losses; gaseous mixtures changing concentrations along the length of dripline). This may place design and operational limits on the use of gas injection on larger and longer SDI systems.

SDI use is increasing in lower-valued commodity crops, such as cotton and corn, and as a result, there is an increased need for lower-cost systems with reliable designs and installations. Manufacturers have responded to this need by providing larger-diameter driplines and driplines with lower nominal flowrates, so that longer lengths of run and larger zone sizes can be designed with high uniformity. These larger-diameter driplines, although costing more per unit length, can often result in a less expensive installation through reduction of trenching and system controls. Dripline diameters up to 1.375 inches are now available and are often used in the larger fields to decrease the number of required zones and obstructions posed by additional valve boxes. Each SDI system design is different, however, and the grower should not automatically choose the larger dripline diameter. Larger driplines require longer fill and drain times, which can adversely affect water and chemical application uniformity and redistribution within the soil. Chemigation travel times for the larger-diameter driplines can exceed the period of the planned irrigation event on coarse-textured soils and thus lead to leaching and/or improper chemical application. The nominal dripline flowrate can be reduced by reducing the emitter discharge or by increasing the emitter spacing. Physical limitations exist on reducing emitter discharge because smaller passageways are more easily clogged. There also are limitations on increasing the emitter spacing related to adequately supplying the crop its water needs. Driplines with lower emitter discharges of 0.13 to 0.24 gal/h and larger emitter spacing of 12 to 24 inches are economically attractive (reduced design and installation costs) on deeper, medium-textured soils for crops with extensive root systems.

SDI system component issues

The wall thickness of SDI driplines is often greater than for DI because of the added risk of dripline damage during installation and because the SDI system is usually planned to have an extended, multiple-year life. In situations where soil compaction or soil overburden may cause dripline deformation, thick-walled tubing (hard hose) may be selected. Thicker-walled products allow higher maximum dripline pressures that can be used to open partly collapsed driplines caused by soil compaction or overburden, or to increase flow of chemically treated water through partly clogged emitters. In addition, there have been anecdotal reports of greater insect damage to driplines with thinner walls. The thin-walled, collapsible driplines (commonly referred to as drip tapes in the United States) also are used extensively in SDI. In most cases for SDI, wall thicknesses of 254 to 635 µm are selected instead of the thinner-walled models often chosen for single-year use in DI. Some concerns have been raised on waste plastic product (driplines) in the subsoil when the SDI system is abandoned.

System component reliability, durability, and ease of installation and repair become significant quality and maintenance-control concerns when the system is underground, where leaks and other problems are difficult to detect, find, and repair (Lamm et al., 1997b). A multitude of dripline connectors and connection procedures are commercially available. Selection of a connector that properly matches the dripline characteristics with an easy and reliable connection procedure is important for ensuring a successful installation. Because of the variation in individuals' ability to make watertight connections, quality control and assurance are recommended during installation. The connections should be pressure-tested with water to locate leaks before the trenches are backfilled. Thus the pump and filtration system must be operational before SDI installation.

SDI systems require additional components that are either not required or not used to the same extent for other types of microirrigation systems. Flushlines are header or manifold pipelines installed at the distal end of the zone that allow for jointly flushing of a group of driplines. In addition to flushing, the flushline also serves to equalize pressure between driplines during normal operation and to reduce the potential for entry of soil-laden water by providing positive water pressure on both sides of a severed dripline. It should be noted that the flushline allows for the convenient flushing of a group of driplines but does not increase the effectiveness of flushing. Hydraulically, it is more effective to flush a single dripline, and, as a result, flushlines are not typically used on the high-valued perennial crops such as grapes and tree crops. Air/vacuum relief valves are required on all irrigation systems, but are needed to a greater extent on SDI systems to minimize backsiphoning of water into the emitters.

Clogging of emitters by soil ingestion caused by backsiphoning at system shutdown can occur with SDI and does not usually occur with DI. Prevention of soil ingestion in SDI is usually approached through installation of air/vacuum relief valves at the high elevation points in the system and through improved emitter characteristics, such as closing slits or flaps that may provide a “checkvalve” feature at shutdown. Some manufacturers have changed dripline designs in attempts to reduce or eliminate this problem. Continued improvements in emitter design that limit soil ingestion will be an important factor in adoption of SDI on undulating soils, where the addition of sufficient air/vacuum relief valves can be a significant design impediment due to added cost and/or system complexity.

Instances have been reported of soil being trapped under the elastic membrane in pressure-compensating (PC) emitters that results in unregulated flow. PC emitters are sometimes not used for SDI for this reason. Root intrusion can also be a problem for SDI and some manufacturers have responded altering dripline and emitter physical characteristics or through addition of chemical inhibitors

Challenges with Soil Types and Characteristics

Soil Overburden and Compaction Issues

Driplines can be deformed by soil overburden and/or compaction that will decrease flowrates and reduce system uniformity. This is especially true for thin-walled driplines. Compression of driplines from their normal circular shape into an elliptical shape increases the friction head loss and thus will reduce the flowrate from the design condition (Hills et al., 1989). The flowrate reduction can become significant when the amount of compression is great (Fig. 2). When soil compaction is likely to occur, dripline lengths may need to be reduced to maintain the initial system uniformity. SDI system operation for extended periods (Hills et al., 1989) and initiation of the system after large precipitation wetting events can remediate some of the dripline compression problems by reducing soil compaction in the immediate vicinity of the dripline. Soil compaction can be avoided by limiting mechanized field operations when soil water conditions are most conducive to compaction (i.e., usually slightly drier than field capacity for many soils). In bridging soils, deeply placed driplines are usually less susceptible to compression by soil compaction. However, in nonbridging soils, soil overburden at deeper depths is a concern for SDI systems. The problem of overburden in sandy soils may require the use of heavy-walled, compression-resistant driplines (hard hose) instead of the less expensive thin-walled, collapsible driplines used in many systems.

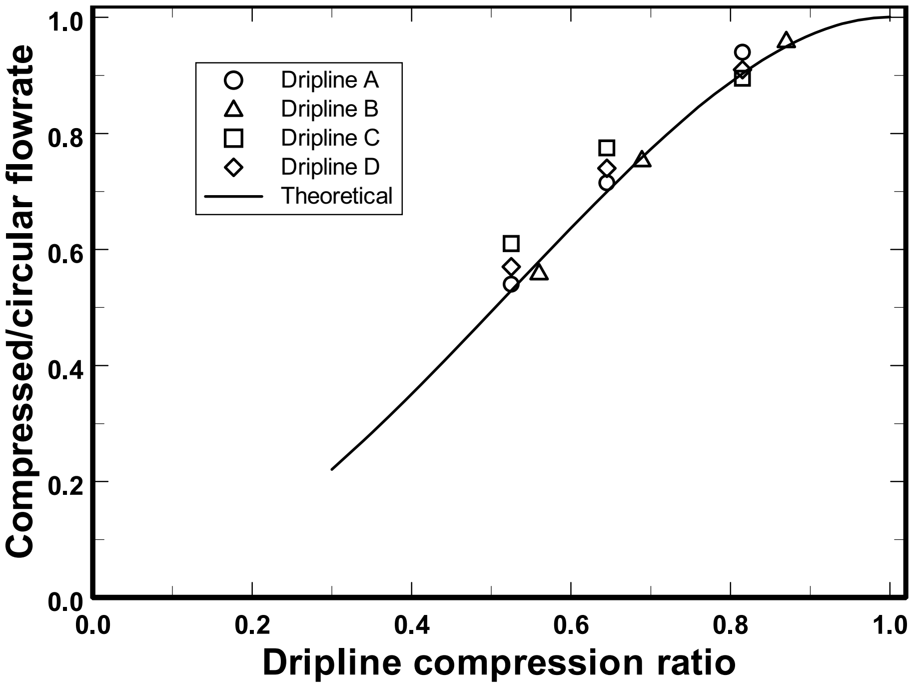

Figure 2. Decrease in flowrate resulting from deforming a circular cross-section into an elliptical cross-section. The dripline compression ratio is equal to the minor axis of the elliptical (compressed) dripline divided by the original circular dripline diameter. The solid line represents the theoretical relationship, and the data points are for the four driplines tested. After Hills et al. (1989).

Reduced Upward Water Movement and Seed Germination Concerns

Adequate soil water for crop germination with SDI is important in semiarid and arid regions and in other regions prone to drought during crop establishment. Germination may become a problem depending on the installation depth and soil properties. This may be particularly troublesome on soils with vertical cracking or for coarse-textured soils and shallowly planted seeds. Salt accumulation may be increased above the dripline, thus creating a salinity hazard for the emerging seedlings or small transplants. Dripline depth is important in affecting the surface and near-surface soil water conditions with shallower dripline depths providing wetter conditions. Tillage and planting practices can sometimes be used to prevent or avoid dry soil conditions for crop germination and establishment. When applied irrigation does not move into the loosely consolidated soil surface layers in a bed cropping system, the dry soil can be removed to the traffic furrow, thus exposing wetter and firmer soils for crop establishment. Using emitters with a greater discharge rate also can improve soil water conditions for crop establishment but may negatively affect system design and installation costs and exacerbate soil water surfacing. Pulsing the SDI system, which involves applying small increments of water multiple times per day rather than applying a larger amount for a longer duration, has been advocated as a procedure to improve surface and near-surface wetting for crop establishment. Although considerable research and theory to support this technique for improved wetting patterns are available for DI (Zur, 1976; Levin and van Rooyen, 1977; Levin et al., 1979), little research and few operational guidelines exist for SDI.

Soil/Application Rate Interactions

Water redistribution may be too low on coarse-textured soils, resulting in a limited wetted zone. This particularly may be a problem for tree crops with their extensive root system which may necessitate selection of an alternative irrigation system or installation of more driplines for each crop row.

In some situations, the SDI emitter discharge is greater than the saturated hydraulic conductivity of the soil in the immediate vicinity of the emitter leading to backpressure on the emitter which can cause irrigation uniformity problems that can have both an irrigation system aspect and a soil water redistribution aspect. Application of biological effluents through the SDI system may exacerbate these problems by blocking soil pores or through chemical changes to soil properties. SDI system uniformity can be reduced when the soil is unable to redistribute water away from the emitter fast enough to prevent backpressure on the emitter. Reductions in emitter discharge of 9.5, 17.5, and 29.6% due to backpressure were calculated for design emitter discharges of 0.26, 0.53, and 1.06 gal/h, respectively, for the hydraulic properties of a sandy loam in Israel (Warrick and Shani, 1996). This resulted in corresponding Christiansen's uniformity (UC) values of 95, 91, and 85 for the SDI system. When the emitter discharge increases or the soil hydraulic conductivity decreases, the pressure head increases around the emitter and reduces the emitter discharge, depending on the severity of the mismatch between the emitter and soil characteristics. Soil type, emitter discharge, presence of cavities around the emitter, and SDI system hydraulic properties were listed by Shani et al. (1996) as the controlling factors for the existence of backpressure and the subsequent emitter flow reduction. In a preliminary study, they reported emitter discharge reductions of as much as 50% were attributable to backpressure. Modeling procedures to account for the effect of backpressure on emitter discharge have been developed by Lazarovitch et al. (2005).

Soil water redistribution may be adversely affected by the backpressure phenomenon. The applied water from the emitter discharged with a pressure greater than atmospheric may also seek a path of least resistance to release its energy. Sometimes the path of least resistance is upwards and the water will travel to the soil surface causing differential soil water redistribution, wet spots that may interrupt farming operations, increased soil water evaporation, and possibly irrigation runoff. This "surfacing" phenomenon also may be directly associated with a "chimney effect" in which small, fine soil particles are carried to the surface in the preferential flow path or macropore. The sorting of soil particles and deposition into the walls of the chimney will further reinforce the preferential flow path and surfacing may become worse. These depositional crusts that are formed within the soil profile can have hydraulic conductivities that are reduced by 2 to 3 orders of magnitude (Shainberg and Singer, 1986; Southard et al., 1988). The chimney can be disrupted by tillage, but will often reappear because the flow channel still exists in the region around the emitter which was undisturbed by tillage. The surfacing and chimney effects are somewhat analogous to volcanic activity (Zimmer et al., 1988), and the point where free water exits the soil has even been called a caldera (Fig. 3). Surfacing can be a significant problem on some soil types and is particularly troublesome when it occurs in alfalfa fields resulting in wet spots at harvest (Hutmacher et al., 1992; McGill, 1993). The preferential flow path or macropore does not necessarily exist before installation of SDI. Rather, the macropore can be caused by the SDI-applied water forcing an outlet (Battam et al., 2002). The extent of surfacing is dependent on soil type, dripline depth, and emitter discharge (Zimmer et al., 1988; Shani et. al., 1996; Battam et al., 2002). Decreasing the emitter spacing will allow reduced emitter discharges, while maintaining the SDI system design flowrate and thus may be a primary method of preventing surfacing problems. Using shorter-duration irrigation events (pulsing) may reduce the amount and magnitude of unwanted surface water problems, but may not prevent surfacing (Battam et al., 2002). They suggested that a partial remedy to an existing surfacing problem would be to reduce operating pressures, thus reducing emitter discharge rates.

Figure 3. Caldera resulting from surfacing of water from an SDI emitter in California. Photo courtesy of F. R. Lamm, Kansas State University.

Challenges with Cultural Practices

Tillage and Harvesting Issues

Tillage and other cultural practices can also damage driplines, resulting in leaks that reduce system uniformity. Primary and secondary tillage operations may be limited by dripline placement and depth. SDI systems should be installed at the specified dripline depth uniformly throughout the field so that tillage and cultural practices can be planned to accommodate this depth without causing damage. Because SDI systems are fixed spatially, it is difficult to accommodate crops of different row spacing. Some crops may require very close dripline spacing that may be economically impractical. Additional caution must be taken at the time of annual row-crop planting to ensure that crop orientation and spacing are appropriately matched to dripline location. Ayars et al. (1995) reported an instance where several hundred feet of dripline had to be replaced because the bedding operation damaged dripline that had been improperly placed (inconsistent depth and location). For SDI driplines installed at an 3 inch depth, Chase (1985) reported damage by planting and weeding operations. Shallow driplines can also be damaged by wheel traffic during harvesting in wet soil conditions. Heavy alfalfa-harvesting equipment damaged SDI driplines at a 4-inch depth in Hawaii (Bui and Osgood, 1990), whereas driplines at 14 inches were not damaged. Cultural operations with tractors and harvesters during wet soil conditions may damage driplines in shallow SDI installations, especially if installed in the inter-row area where wheel traffic occurs.

Salinity and Irrigation Management Interactions

Both temporal and spatial soil salinity and water distributions can be important for SDI. Upward water movement from subsurface driplines can create a highly saline zone above the emitters that can be toxic to transplants and seedlings. The same level of salinity at this depth may be of little consequence to an established crop provided that the saline zone does not move into the active root zone. Growers may remediate the problem of salinity in the seeding or transplanting zone by dormant season leaching with precipitation or sprinkler irrigation (Nelson and Davis, 1974). Another method is to build up the crop bed to a greater height than normal, move the salts into this higher peak through irrigation, and then remove the salt accumulation in the peak location through tillage before planting (Hanson and Bendixen, 1993). The management of crop location with respect to dripline location can be important for even moderately saline waters with SDI systems that are used for multiple years unless periodic leaching is provided. Root activity was limited to the wetted soil volume for drip-irrigated tomato and peanut on a sandy soil, but the rooting patterns were different for fresh and saline water (Ben-Asher and Silberbush, 1992). When freshwater was used, a relatively high root density occurred around the periphery of the wetted volume, but with saline water limited root activity existed at the periphery. Most root activity occurred in the leached zone beneath the emitter.

Nutrient Management and Availability

The combined management of water and nutrients is one of the most significant advantages of SDI. Water and nutrients can be supplied in optimum amounts to the most active part of the crop root zone, with timing appropriate for maximum plant response, while minimizing the potential for nutrient leaching. However, smaller root zones can make irrigation and fertilization critical issues from both timing and quantity perspectives. The restricted volume may not be sufficient to supply water to the plant so that diurnal crop water stresses can be avoided. Application of nutrients through the SDI system may be required for optimum yields. Application of micronutrients may also become more critical because the smaller soil volume is depleted of these nutrients in a shorter time.

Fertilizer applications for most crops are most effective when applied at the latest possible date compatible with quick uptake by the plant. The key point is providing the fertilizer in a readily available form in the presence of the crop root system. Subsurface drip irrigation can effectively manage the placement and availability of both soil mobile and immobile nutrients. Phosphorus fertigation with SDI can increase plant nutrient uptake, root growth and crop yield. Application of P through SDI accomplishes more than just placing the P at the center of the crop root zone. Continuous P fertigation allows uptake of this relatively immobile nutrient through mass flow to the plant roots rather than just the roots growing and coming in contact with fixed P within the soil profile (Bar-Yosef, 1999). However, care must be exercised when applying P through microirrigation systems to avoid emitter clogging. This requires using appropriate P formulation and careful attention to water chemistry. Similarly, nitrogen fertigation with SDI can also be beneficial in plant nutrient uptake, root growth or crop yield, and environmental protection. Some forms of N are readily leachable, so SDI can be a good tool for timely applications with precise placement in the crop root zone. Plants are capable of direct uptake of both ammonium- and nitrate-N. Ammonium-N is held on the cation exchange complex and is relatively unleachable, whereas nitrate-N is free to move with the soil water solution. The nitrogen fertilizer solution urea-ammonium nitrate (UAN, 32-0-0) is not only very water soluble for SDI injection (reduced emitter clogging hazard), but also contains approximately 25% nitrate-N, 25% ammonium-N, and 50% urea-N (reduced in the first step to ammonium-N). Subsurface drip irrigation of water containing UAN (32-0-0) supplies both the readily absorbed nitrate-N and the less mobile ammonium-N, which can be absorbed directly by the plant or microbially transformed to nitrate-N. Combined management of irrigation and anticipated rainfall has long been a necessary tool to manage nitrogen fertilization on sandy soils. An untimely rainfall event, coupled with a fully recharged soil profile, can lead to the loss of a significant portion of the soil N. Under dry climatic conditions it may become necessary to apply at least a portion of the required crop N through the SDI system to prevent N applied to the soil surface from becoming positionally unavailable to the crop because the active root zone is deeper in the soil nearer the point of water application (Fig 4).

Figure 4. Subsurface drip-irrigated field corn experiencing nitrogen stress due to dry surface soil conditions despite having abundant nitrogen reserves in the soil surface layers from surface application of N. The SDI driplines in this field were installed at a depth of 16 to 18 inches. The situation was later remedied by application of some N through the SDI system.

Challenges with Differential Crop Response

Some crops may perform better under SDI than others and some crops may present challenges to SDI system maintenance. For example, some crops such as sweet potato, celery, asparagus and permanent crops that have a long period when irrigation is minimal or terminated, may exhibit high root intrusion into SDI emitters (Burt and Styles, 1999). Although peanuts are successfully grown with SDI in some regions (Sorenson et al., 2001), the plant process of pegging can be inhibited in arid regions and in cracking soils (Howell, 2001). Root crops such as potato and onion can present unique crop harvest challenges for SDI, and, as a result, may not be good candidates for continuous, multiple-year SDI systems, although efforts have been made to overcome these obstacles (Abrol and Dixit, 1972; DeTar et al., 1996; Shock et al., 1998).

While crop transpiration for a well-watered crop does not vary across irrigation systems, differences can exist in the ability of alternative irrigation systems to provide a consistently well-watered condition that matches plant growth and the economic yield formation needs of the crop. In essence, the extent to which the conditions match a well-watered condition could differ spatially within the crop root profile and also could differ temporally on diel or longer timescales.

The presence of a consistently and adequately wetted root zone can be especially important for crops that develop yield below the soil surface. Increased soil water availability and reduced soil strength on soils wetted by SDI were contributing factors in higher onion yields in India (Abrol and Dixit, 1972). Potato yield was increased 27% with SDI over sprinkler irrigation while reducing irrigation needs by 29%, provided there were driplines in each crop row (DeTar et al., 1996). Their results indicated that very little water would be wasted using a high frequency, every-row SDI system and that the system could closely match the actual potato transpiration needs. Nutrient availability, mobility, and plant uptake can also be enhanced under the SDI-controlled wetted volume near the center of the crop root zone (Bar-Yosef, 1999). Conversely, when the controlled wetted volume is not matched well to the crop root zone, SDI can be a poor irrigation method. Tomato yields were decreased 30% when using SDI, compared with DI, on a sandy soil in Florida (Clark et al., 1993) where deep percolation was excessive for this shallow-rooted crop.

Greater corn grain yields were reported for SDI in three normal to wetter years in Kansas (Fig. 5), but LEPA (low energy precision application) obtained greater yields in four extreme drought years (Lamm, 2004). The differential yield response was attributed to differences in the corn yield components. Greater LEPA corn yields (approximately 15 bu/acre) were associated with greater kernels/ear as compared to SDI (534 vs. 493 kernels/ear) in the extreme drought years. Greater SDI yields (approximately 15 bu/acre) were associated with greater kernel mass at harvest as compared to LEPA (347 vs. 332 mg/kernel) in normal to wetter years. The reason for these differences has not been determined, but new studies are underway.

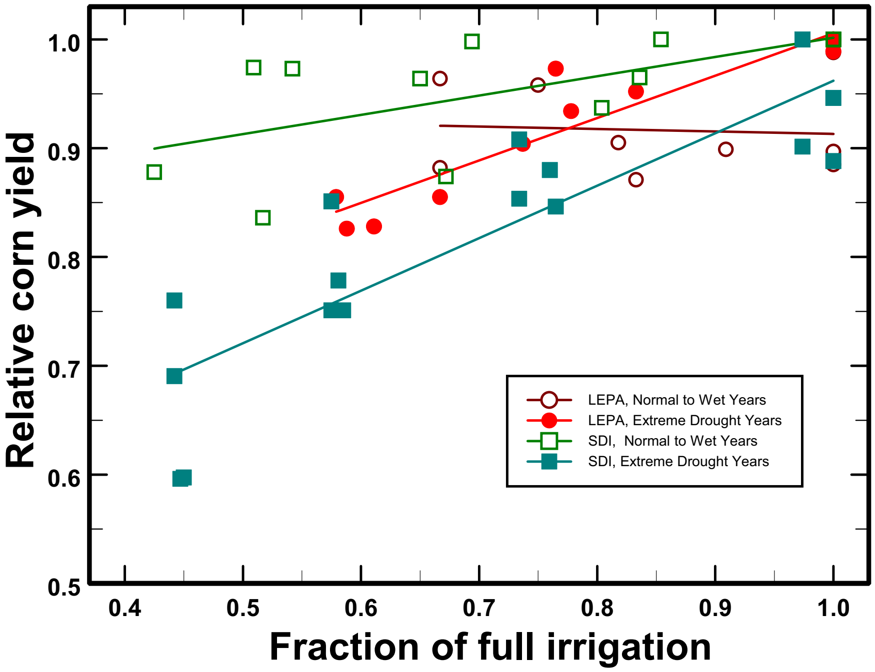

Figure 5. Corn grain yield as affected by irrigation system type (LEPA sprinkler and SDI) for various irrigation regimes in normal to wetter years and extreme drought years, KSU Northwest Research-Extension Center, Colby, Kansas.

Challenges with System Maintenance

Filtration and Dripline Flushing

As with all microirrigation systems, water filtration is critical in ensuring proper system operation and system longevity. However, this issue becomes even more important for long-term SDI systems where duration of greater than 10 years is desired. SDI may require more complex water quality management than surface microirrigation systems because there are no opportunities to clean emitters manually. The added cost of complex water filtration and chemical treatment of marginal-quality water might further reduce the feasibility of SDI use on lower-value crops.

Accumulated sediments must be periodically flushed from the SDI system. In many instances, the assurance that adequate water flushing velocities can be obtained throughout the proposed SDI system will be the controlling factor in the sizing of irrigation zones, pipelines, driplines, and emitter discharges (Burt and Styles, 1999). The flushing requirement and associated components add considerable complexity and cost to the SDI system, but are integral to a successful system. The ASABE recommends a minimum flushing velocity of 1 ft/s (ASAE EP-405) but some publications recommend greater flushing velocities for SDI because it is below ground. However, it must be noted that greater flushing velocities will increase system cost and reduce zone size. Flushing velocities greater than 1 ft /s did not have large effects on emitter clogging or emitter discharge in an SDI study in Kansas (Puig-Bargués et al., 2009).

Mechanical and Pest Leaks

Mechanical (system installation and crop tillage) and pest (burrowing mammals and insects) damage can cause leaks that reduce system uniformity when they are not located and repaired. Minor leaks on deeper SDI systems may not wet the soil surface, and may be discovered only by a chance observance of differential plant growth along the damaged dripline during the growing season. Large leaks are easier to locate than small ones, particularly when no crop is present. Many growers routinely start their SDI system before the cropping season to inspect for leaks and make repairs. Holes in the dripline can allow soil and debris to enter the dripline, decreasing the flow in the larger dripline chamber and possibly clogging other emitters downstream. Successful repairs and/or remediation depend on the early detection of problems. Fully or severely clogged emitters are much more difficult to remediate than partially clogged emitters (Ravina et al., 1992). Rodent damage can also be reduced when the problem is recognized early, and steps are taken to reduce rodent habitat and activity in the field.

Burrowing mammals, principally of the rodent family, can cause extensive leaks that reduce system uniformity. Most rodents avoid digging into wet soil, so dripline leaks presumably are not caused by the animals looking for water. Rather, rodents must gnaw on hard materials, such as plastic, to wear down their continuously growing teeth. The difficulty in determining the actual location of a dripline leak caused by rodents is compounded by the fact that the leaking water may follow the burrow path for a considerable distance before surfacing. Anecdotal reports from the U. S. Great Plains can be used to describe some of the typical habitat scenarios that tend to increase rodent problems. These scenarios include the close proximity of permanent pastures and alfalfa fields, railroad and highway easements, irrigation canals, sandy soils, crop and grain residues during an extended winter dormant period, or absence of tillage.

Cultural practices such as tillage and crop residue removal from around SDI control heads and above-ground system apparatus seem to decrease the occurrence of rodent problems. Some growers have tried deep subsoiling and/or applying poison bait around the SDI system field perimeters as a means of reducing rodent subsurface entry into the field. Isolated patches of residue within a barren surrounding landscape will provide an "oasis" effect conducive to rodent establishment. After the smaller rodents become established, other burrowing predators such as badgers can move into the field, further exacerbating the damage. Caustic, odoriferous, pungent, and unpalatable chemical materials have been applied through SDI systems in attempts to reduce rodent damage, but none of these trials has obtained adequate control. Periodic wetting of the soil during the dormant period has been suggested as a possible means of reducing rodent damage. Deeper SDI depths (18 inches or greater) may avoid some rodent damage (Van der Gulik, 1999). Many of the burrowing mammals of concern in the United States have a typical depth range of activity that is less than 12 inches (Cline et. al., 1982).

Burrowing insects can cause dripline leaks that decrease system uniformity. Several incidents of wireworm damage to SDI systems have been reported in the United States. These reports indicated that the damage is most often associated with the initial SDI system installation period and with a delay in wetting the soil after installation. Some growers irrigate immediately after installation, and others have injected fumigants and insecticides to prevent wireworm damage (Burt and Styles 1999). The use of insecticides through SDI systems to control insects that cause leaks is a controversial environmental practice because of possible grower health hazard when repairing any remaining leaks. Growers should always read and carefully follow the pesticide label and precautions. Wireworm activity is usually greatest at the 8 to 14 inch depth (Bryson, 1929), so deeper SDI system installation may help to prevent wireworm damage.

Root Intrusion and Root Pinching

Root intrusion and root pinching of the dripline are unique problems to SDI that can reduce system uniformity. Although these SDI problems have long been recognized, few published, detailed research studies are available. In a literature review of SDI, Camp (1998) cited only 4 of 61 reports that provided management guidelines discussing root intrusion.

Root intrusion tends to be of greater significance under some crops than others. Perennials often present root intrusion problems when roots continue to grow and utilize some water in winter or semi-dormant periods when irrigation is usually not practiced (Schwankl et al., 1993; Hanson et. al., 1997). Root intrusion can become a serious problem in a very short time (Fig. 6). Bermuda grass has caused serious root intrusion problems in less than one year (Suarez-Rey et. al., 2000).

Coelho and Faria (2003) measured root intrusion of coffee and citrus roots into 14 different emitter models placed in containers. Although all tested emitters experienced root intrusion under the harsh conditions of this container study, there were differences in the overall effect on flowrate and variability. They concluded that nonpressure-compensating emitters performed better than pressure-compensating emitters. Pressure-compensating emitters tended to be unstable, initially increasing, and then decreasing the average flowrate when the emitter became clogged with root and soil particles. Nonpressure-compensating emitters were stable, gradually decreasing the average flowrate as roots and soil particles began to clog the emitter. Ingestion of soil was correlated with increased root intrusion. Emitters that undergo gradual flowrate reduction display more advance warning to the grower, who can then alter irrigation management or use chemical methods to prevent or remediate the root-intrusion problem. Root intrusion may disturb or distort the shape of the elastic membrane on pressure-compensating emitters and thus exacerbate flowrate variations. They also noted that root intrusion was greatest under dry conditions as listed in numerous publications (Schwankl et al., 1993; Hanson et al., 1997; Burt and Styles, 1999; Van der Gulik, 1999). Most crop roots do not grow into saturated soils. Consequently, frequent SDI can create a small saturated zone around the emitter that will deter root intrusion. Celery is an exception to this rule, and thus some growers prefer DI or have used chemicals to prevent root intrusion (Schwankl et al., 1993; Hanson et al., 1997). Coelho and Faria (2003) concluded that there was no preferential growth toward the emitter orifice within the wetted soil volume and that root intrusion was just the result of random exploration. However, the ingestion of soil was correlated with increased root intrusion which may lead to capillary formation directing the hair roots towards the emitter opening.

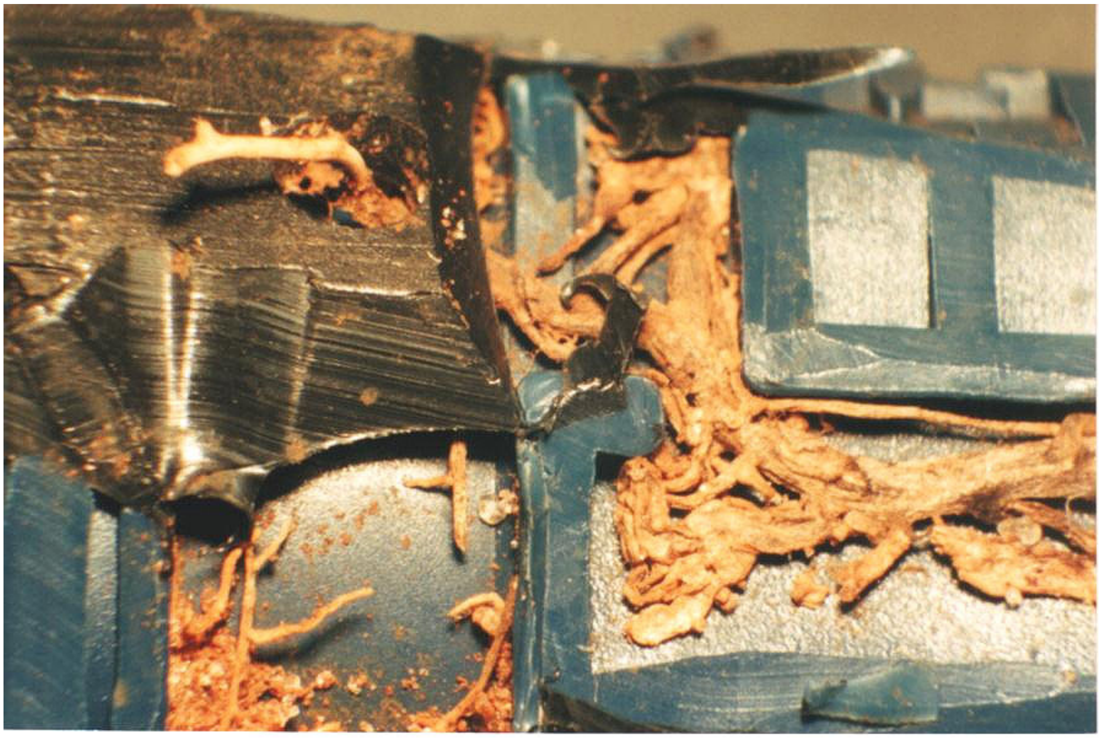

Figure 6. Single coffee plant root entering an emitter can enlarge into a large root mass once inside the emitter and dripline. Photo courtesy of Rubens Duarte Coelho, University of Sao Paulo, ESALQ / Brazil.

The extent of root intrusion varies with different dripline and emitter construction techniques (Bui, 1990). Manufacturers that still use seamed construction have tended to discontinue placing the emitter orifices in the dripline seam because this has been noted as a common root path, once it is located by random root exploration (Schwankl et al., 1993). Manufacturers are marketing a variety of emitter design techniques to avoid root intrusion, such as closing flaps, closing slits, raised protrusions that deflect roots, or oversized water outlets that protect the much smaller emitter orifices below.

Chemical protection of the emitter with herbicide (trifluralin) is another good method of preventing root intrusion. Ruskin and Ferguson (1998) discussed the three primary trifluralin herbicide methods in which the herbicide is injected directly into the irrigation water, incorporated into the emitter at manufacturing, or incorporated into the filter components. Trifluralin acts by stopping cell growth as the root tip encounters the herbicide, but does not kill the plant when properly used for root intrusion (Zoldoske, 1999). Careful and safe use of these herbicide methods according to label instructions is necessary to protect the environment from contamination while attempting to reduce the root-intrusion hazard. The use of acids, acid-based fertilizers, and chlorine may also help to prevent root intrusion or help to remediate partially clogged emitters by oxidizing the roots (Schwankl et al., 1993; Burt, 1995; Hanson et al., 1997; Ayars et al., 1999; Burt and Styles, 1999; Van der Gulik, 1999).

Tree and grape vine roots can grow around and pinch SDI driplines, which either greatly reduces or stops flow in the dripline (Fig 7). This phenomenon has reduced the effectiveness of some SDI systems in California (Burt and Styles, 1999).

Figure 7. Subsurface dripline pinched by peach tree root in California, USA. Photo courtesy of T. Trout, USDA-ARS, Parlier, California.

Challenges with System Monitoring and Operation

Emitter discharge can be affected by clogging (internally from physical, chemical, or biological hazards or externally from soil ingestion caused by backsiphoning), root intrusion, root pinching of the dripline, leaks caused by mechanical or pest damage, soil overburden and/or compaction, soil hydraulic conductivity, and related parameters. Qualitative information about irrigation system uniformity can be continually observed from surface wetting with DI, but this is not true for SDI. Water applications with SDI may be essentially invisible so that it is more difficult to evaluate system operation and application uniformity. There have been cases where producers revert to DI because of the uncertainty of SDI system performance or have intentionally overirrigated with SDI so that they can verify system operation (Fig. 8).

Figure 8. Example of overirrigation of almonds with SDI (right tree line) and the resulting dampening of soil and weed establishment, so that the grower was assured of SDI system operation. A better solution would have been to carefully monitor flowmeters and pressure gauges for the SDI system. Photo courtesy of L. Schwankl, University of California-Davis.

System mismanagement can lead to underirrigation, with reduced crop yield and quality, or overirrigation, with poor soil aeration and deep percolation problems. Careful monitoring of system flowmeters and pressure gauges is required to determine that the system is operating properly. Record keeping is an important aspect in monitoring and ensuring the long-term performance of SDI systems because there are fewer easily observable indicators of performance than with DI. Flowmeters, pressure gauges, and other system operational sensors (e.g., automated backflush controllers, soil water sensors) are used to monitor SDI system operation and performance. Baseline flowrates and pressures for each irrigation zone should be determined at the initiation of new SDI systems. A deviation from these flowrate and pressure baselines, which occurs either abruptly or gradually as part of a trend, is a signal to the grower that a problem (clogging, root intrusion, or a leak) is occurring. An example of how good records can be used to diagnose hypothetical SDI problems can be found in any of the three following references (Lamm and Camp, 2007; Lamm and Rogers, 2009; Rogers and Lamm, 2009).

The volume of soil wetted by the emitter may be too limited on coarse-textured soils and system capacity and system reliability can be extremely critical issues because there is less ability to buffer and overcome insufficient irrigation capacity or system breakdown.

Conclusion

Subsurface drip irrigation can be adapted to a wide variety of cropping systems in many diverse regions. The success of SDI depends on water managers, designers, equipment distributors, irrigation consultants and the end-user in understanding the concepts and managing some of the unique challenges it presents. In some cases, alternative irrigation systems can be a much better choice for the enduser when these challenges are difficult to handle.

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[1] Mention of tradenames is for informational purposes only and does not constitute endorsement by the authors or by the institutions they serve.

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Using SDI to effectively irrigate with biological effluent

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Abstract. *Subsurface drip irrigation is a viable method for irrigating with biological effluent. Proper care must be exercised in the design and management of the SDI system to prevent emitter clogging and the resulting poor system performance or complete loss of the irrigation system. The proper precautions can be categorized into: 1. Select the proper components (emitters), 2. Filter the effluent adequately, 3. Suppress biological growth and chemical precipitation, 4. Flush the driplines occasionally, and 5. Monitor the system so small problems don't become large problems. This paper summarizes some of the recent research addressing those five steps. Recent research is developing emitters that are less susceptible to clogging by refining the flow path length, cross-section flow area, internal emitter geometry, and other factors. Biofilm research is identifying the mechanisms of biofilm formation and clogging, thus creating a path to potential solutions to clogging because of biological hazards. Filter testing studies are identifying which filter technology is providing adequate protection of the emitters and outlining filter and backwashing management recommendations. Biological control has historically been accomplished with chlorination; that technology is mature and effective. Biological control with antagonistic bacteria also holds promise for prevention of emitter clogging due to biological activities. Flushing has been a standard practice but has received little research focus until recently. Finally, advances in controls, sensors, and data communications will make remote monitoring and automation more practical and widespread.*

Keywords. Subsurface drip irrigation, SDI, biological effluent, wastewater, emitter clogging

Introduction

Biological effluent, sometimes called wastewater, can be an important resource in many areas. Some sources of biological effluent include animal production facilities, municipalities, and households. The efficient use of biological effluent for irrigation brings many advantages (Trooien and Hills, 2007; Gushiken, 1995). Using subsurface drip irrigation (SDI) brings even more advantages. Those advantages are exploited in many ways and in areas, including various locations in the United States and many locations worldwide, from Argentina to Tunisia (Asano et al., 2006). One advantage of using SDI is the nitrogen losses are reduced compared to simulated low energy precision application (LEPA) of the effluent (Lamm et al., 2007). This results in reduced leaching and volatilization and a greater percentage of the nitrogen in the effluent available to the crop, even though increased uptake was not measured.

Prevention of emitter clogging is the key to long irrigation system life. Emitters can be clogged due to biological, physical, or chemical processes. Recent evidence points to biofilms as a major cause of biological emitter clogging (Cararo et al., 2006). Yan et al. (2009) used scanning electron microscopy to show that biological clogging was caused by particles and extracellular polysaccharides that combined to clog emitter pathways. Additionally, physical clogging can be caused by sediment getting caught in the corners of the tortuous flow pathway (Cararo et al., 2006). Effluents often have high solids concentrations. Finally, chemical precipitation can also cause clogging when irrigating with effluents (Liu and Huang, 2009).

To effectively irrigate with effluent using microirrigation in general, and SDI in particular, requires appropriate protection of the system to prevent emitter clogging. Five steps have been identified to adequately protect the emitters from clogging (Trooien and Hills, 2007). They are:

1. Select the proper components (emitters),
2. Filter the effluent adequately,
3. Suppress biological growth and chemical precipitation,
4. Flush the driplines occasionally, and
5. Monitor the system so small problems don’t become large problems.

This paper will summarize some of the recent research addressing the five steps. The focus will be on research since the development of Trooien and Hills (2007).

Component (emitter) selection

Many different emitters and emitter types have been evaluated for their suitability for use with effluents. Some of the emitter characteristics most often cited as important for clogging prevention are flow path length, cross section flow area, and internal emitter geometry. Emitters with shorter flowpaths have been suggested as less susceptible to clogging (Cararo et al., 2006; Yan et al., 2009). Within three different emitter types, degree of clogging was shown to be positively correlated to pathway length (Cararo et al., 2006). Dentate spacing (Fig. 1) was shown to be especially important in preventing physical clogging as a result of testing 16 different combinations of geometries and sizes (Li et al., 2006). Smaller cross-section flow area has been shown to be a greater risk for biological clogging (Li et al., 2009) and chemical clogging (Liu and Huang, 2009). Dentate angle and height were also important factors but combinations were more important than maximizing any one specific factor. In addition, asymmetrical dentate structures within the emitter may be less susceptible to clogging (Yan et al., 2009). The best performing emitters for applying effluent consisted of a flat body style with a rectangular elastic membrane (pressure compensated and self-cleaning device) and relatively short pathway (Cararo et al., 2006). It is interesting to note that a pressure-compensated emitter that performed well under the testing of Cararo et al. (2006) also showed flow rate reduction of only 7% after 4 years of operation in a field study (Lamm et al., 2002) and performed well in another field test (Duran-Ros et al., 2009a).

Emitter manufacturing method has also been noted as a factor in clogging susceptibility. Two of the four tested molded and welded emitters were more susceptible to clogging than were pressure-compensated on-line emitters (Duran-Ros 2009a). The susceptible molded emitters included a pressure-compensated model and one that was non-compensated and had the smallest cross-sectional flow areas in the test. All emitters had relatively high flow rates (>2 L/hr). Previous studies had noted that molded emitters were less susceptible to clogging than were indented emitters. Greater manufacturing variability (measured by CV) also increases the susceptibility to clogging (Li et al., 2009; Liu and Huang, 2009).

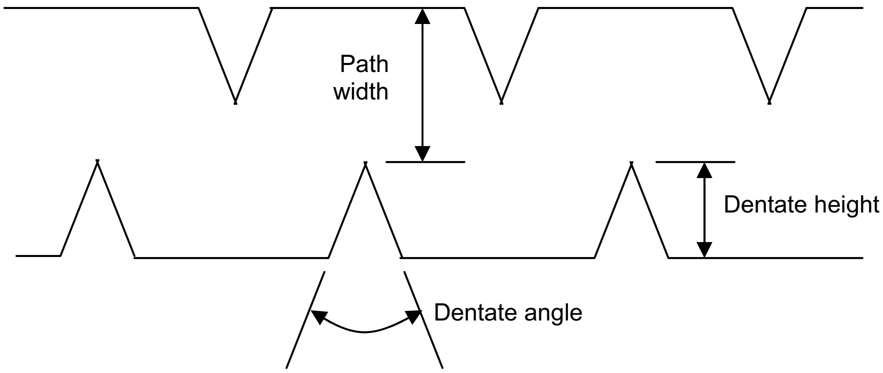

Figure 1. Internal geometry of drip emitter dentate structure (Yan et al., 2007).

Pressure-compensating emitters can have advantages that overcome hydraulic shortcomings that might cause nonuniform flow rates from non-PC emitters caused by pressure changes within the dripline. When water is flowing through a pipe, some pressure change is unavoidable because of the pressure loss due to friction. But even pressure compensating emitters can act as non-pressure-compensating emitters at low pressures (Duan et al, 2008).

Emitters at the distal ends of driplines appear to be more susceptible to clogging when using clean water (Duran-Ros et al., 2009a; Li et al., 2009; Puig-Bargues et al., 2009). However, emitter clogging when using effluent can be more random (Li et al., 2009).

Filtration

Filtration of effluent is especially important because effluents often have higher solids concentrations and biological loads than other water sources. To reduce the hazard of physical clogging, the recommendation of filter opening size of 0.1 times the emitter opening size is still appropriate (Li et al., 2009).

Sand media and disk filters have been used in various implementations of effluent irrigation with SDI. Direct comparisons have shown that a combination of sand and screen filtration protected emitters better than disk or screen filtration (Duran-Ros et al., 2009a). That is, emitters protected by screen and sand filtration had the least reduction of flow rate and the end of the test. Only the sand filtration step actually reduced the solids concentration and turbidity. In fact, screen, disk, and combination of screen and disk filtration- in some cases- didn't reduce solids concentration or turbidity (Duran-Ros et al., 2009a, 2009b). Other reports have demonstrated that relatively lower-cost disk filtration was adequate to protect emitters even through media filtration performed better (Capra and Scicolone, 2005).

To keep any filter operating properly, periodic backwashing is required to keep the filter clean. The time between backwashing operations will vary inversely with the solids concentration of the effluent. This effect is shown in the measurement of pressure differential across disk filters of four opening sizes during the filtration of biological effluent from 10 different animal facilities (Fig 2). As the solids concentration increases, the filter will clog more quickly. Similarly, as the size of the openings in the filter decreases, the filter will clog more quickly and require more frequent backwashing. Filters with very small openings, such as 200 mesh, require very frequent backwashing when filtering the solids contents often found in biological effluents.

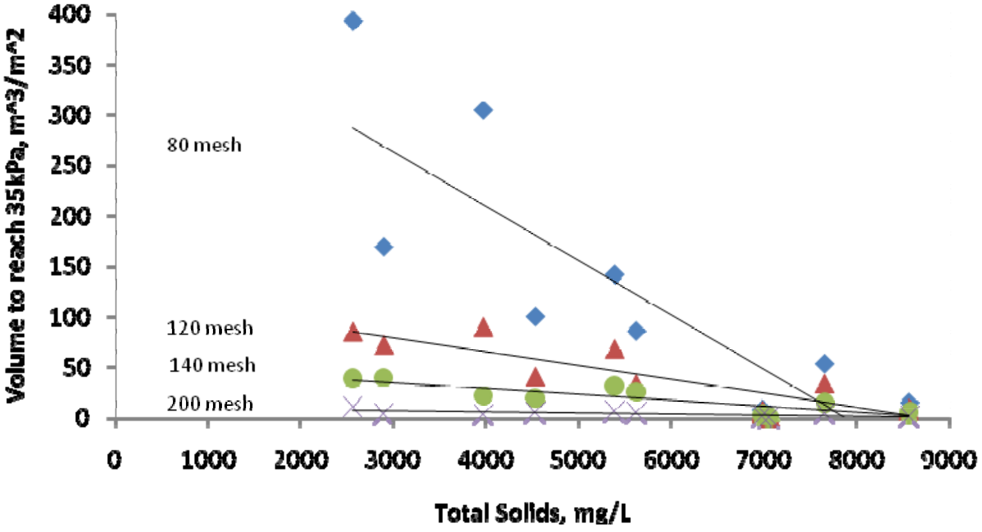

Figure 2. Volume of biological effluent from beef or swine lagoons passing through a disk filter before the pressure differential reaches 35 kPa (5 psi). The mesh sizes are 80 mesh (openings of 200 um), 140 mesh (openings of 130 um), 120 mesh (openings of 115 um), and 200 mesh (openings of 55 um). Each point shown is the average of four replicates. The volume shown is the volume of effluent per area of the filter (unpublished data, Trooien and Lamm, 1999).

Where disk filtration is used, higher backwash pressures (500 kPa, or 72 psi) have been shown to be more efficient, resulting in greater reduction of differential pressure after the backwash (Duran-Ros et al., 2009b). Booster pumps or other hydraulic adjustments may be required to achieve such high pressures in SDI systems.

Suppression of biological growth and chemical precipitation

The most common method of biological control in driplines is chlorination. Chlorination at a concentration of 0.5 g/m^3 has been shown to be effective at preventing ("attenuating") emitter clogging (Cararo et al., 2006). When chlorinating effluents with high ammonia concentrations, additional injections, such as acid, to control pH may be required to get adequate biological control with the chlorine. Many animal effluents have ammonia concentrations great enough to cause this concern.

Attempted cleaning with compressed air at a relatively low pressure of 1.96 kPa (0.3 psi) was not effective for clogging prevention (Cararo et al., 2006). Higher pressures such as 490 to 980 kPa (70 to 140 psi) may be more effective (Keller and Bliesner, 1990) but extra care and safety measures will be required at such high pressures. Some materials, such as thin-walled driplines (tapes) may not be able to withstand these pressures so this method may not be appropriate for them.

If the cause of emitter clogging is biological, another potential cleaning method is the use of antagonistic bacteria (Sahin et al., 2005). Two strains of Bacillus and one strain of Burkholdria were tested against 25 fungi isolates and 121 bacterial strains from greenhouse driplines known to have clogged emitters. The isolated fungi and bacteria were used to clog a 12-m dripline under laboratory condition. Solutions containing the antagonistic bacteria were introduced to the tested dripline two different times, 48 hours apart. After 14 days of daily operation, the flow rate of the tested dripline had recovered from about 5% (nearly completely clogged) to 100% of design flow rate. The flow rate of the control (untreated) dripline did not change during the same time period.

Dripline flushing

Adequate velocity within the dripline is required for a flushing operation to transport sediment to the end of the dripline. The flushing velocity often recommended is 0.3 m/s (ASAE, 2003). That recommendation holds for SDI systems that apply effluent, although greater velocities appear to be able to remove more sediment from the driplines.

When flushing sediment from thin-wall dripline, increased flushing velocity tends to cause increased sediment transport from the dripline (Puig-Bargues et al., 2009). The only statistically significant difference was a single flush at velocity of 0.61 m/s transporting more sediment than did a velocity of 0.23 m/s. Tested flushing velocities were 0.23, 0.3, 0.46, and 0.6 m/s. Although clogging was minimal (the greatest reduction of emitter discharge was only 2.5% of the initial discharge), any clogged emitters were located at the distal ends of driplines. Clogging in this study was physical, caused by sediment in the water. At the end of the study, sediment located within the unflushed dripline was concentrated near the inlet of the dripline even though any clogged emitters were at the distal end of the dripline. Sediment in driplines with lower flushing velocities also tended to accumulate near the inlet but sediment in driplines with higher flushing velocities tended to accumulate at the distal ends of the driplines. They suggested that increasing the flushing duration may be a less complicated and more cost-effective means of improving sediment removal.

Monitoring

Emitter clogging is usually a gradual process. Thus, proper monitoring can detect a clogging issue when it is still minor and recoverable.

The monitoring requirements for continued SDI system operation and maintenance lend themselves well to automation. Automated backwash systems and valve or pump controls have been in operation (e.g. Trooien et al., 2000). But many additional monitoring tasks can be automated. Some of those additional tasks include pressure and flow monitoring in laterals and filters (Duran-Ros et al., 2008). Additionally, systems can be connected to the internet for remote control and access to data (Duran-Ros et al., 2008). This area of application holds much promise for reducing labor requirements of SDI/effluent systems.

Conclusion

Successful irrigation with biological effluent and SDI is possible if the system is properly designed, installed, and managed. Prevention of emitter clogging is essential to keep the system operating properly. Clogging may be caused by biological, physical, or chemical factors. Biofilm research is teaching us more about the structure and formation of biofilms, which will allow us to design and manage systems to avoid such clogging in the future. Implementing the five steps- component selection, filtration, growth and precipitation suppression, dripline flushing, and monitoring- can make successful irrigation possible. Recent research efforts are making progress in all of these areas. Emitter testing and design studies are identifying sizes and geometries that are less susceptible to clogging. Filter research is illuminating the effectiveness of various technologies and outlining management strategies to keep filters operating properly. Chemical injection and biological control research is showing us what works and developing novel control methods. Dripline flushing research is telling us how effective our flushing strategies are and raising possibilities for more efficient and cost-effective flushing methods. Monitoring, control, and communication technologies are enabling advances that can reduce the labor requirements for keeping SDI systems operating properly. These steps and other advances will continue to help us design, install, and manage successful SDI systems to make efficient use of our effluent resources.

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Cotton Irrigation in Kansas

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Abstract: *Kansas is north of the traditional Cotton Belt and considered to be a thermally limited area for cotton; however cotton is being grown as an alternative to corn to stretch declining water resources. Cotton is a non-determinate plant that continues to grow with favorable condition. Irrigation timing is critical to ensure satisfactory crop growth and to achieve boll maturity for favorable lint quality and yield before a killing frost. Both over irrigation or under irrigation may affect yield and quality. Declining water resources make it necessary to conserve water but, at the same time, maintain acceptable revenue. Cotton is a new alternative crop and there is a lack of research based irrigation management information. One year data from a field research on a grower field indicates that 5 inches of irrigation plus rainfall produced a slightly better yield (2.52 bales) compared to an application of 7 inches plus rain (2.31bales). Although the difference is not significant, yet the trend was same for all replications. The treatment receiving only 2.4 inches of water plus the rain produced 1.73 bales, which is significant. Total rainfall during the growing season was 14.31 inches of which 8.81 was considered to be effective rainfall. It was also noticed that the water extraction by roots were mostly within the first 2 feet of root zone; barely reaching to third foot depth. It was also observed that the roots were more laterally distributed rather than deep in depth, although there appeared to be no restricting soil layer.*

Keywords: alternative crop cotton, heat units for cotton,

Introduction: Crop production in western Kansas is dependent on irrigation. The irrigation water source is groundwater from the Ogallala aquifer. The water level of the Ogallala aquifer is declining, causing the depth of pumping to increase. The additional fuel consumption required for greater pumping depths and higher energy costs have resulted in increased pumping costs in recent years. Because of declining water levels and higher pumping costs, the growers are looking for alternative crop that may provide somewhat acceptable revenue at a lower water requirement. Cotton has made some inroads from south moving northward as an alternative crop. Acreage grown in 2006 reached to 110 thousand acres, which has gradually come down due to recent commodity price changes. Most of the crops grown are still in southern counties within Kansas.

Procedures: A producer’s field with center-pivot sprinkler irrigation system was selected for the study. The soil belongs to Richfield series and the texture is silt loam. Three outer spans were selected to establish three replication of the study. Three sets of eight nozzles in each span were fitted with a closing valve to establish three irrigation treatments. The nozzles are five feet apart giving a length forty feet in each set of eight nozzles for individual plots. A width of forty was marked to establish 40 ft by 40 ft individual plots.

The total number plots were nine. Three irrigation treatments in terms of timing and number were randomly scattered in these nine plots. Treatment T1 was set for four irrigation of one inch application depth each time during the growing season. The tentative timing of irrigation was set for July 10, July 20, August 1, and August 10. However, this was changed to meet the field condition and an application of 1.6” inches were applied as pre-irrigation to make the soil water condition suitable for planting and was followed by an application of 0.8” inches after seeding to secure good germination. This was done for all the plots in the trial. Afterwards, T1 received five irrigations starting on June 12 as the first differential treatment (Fig. 1). Total irrigation application amounted to 7” inches for the growing season.

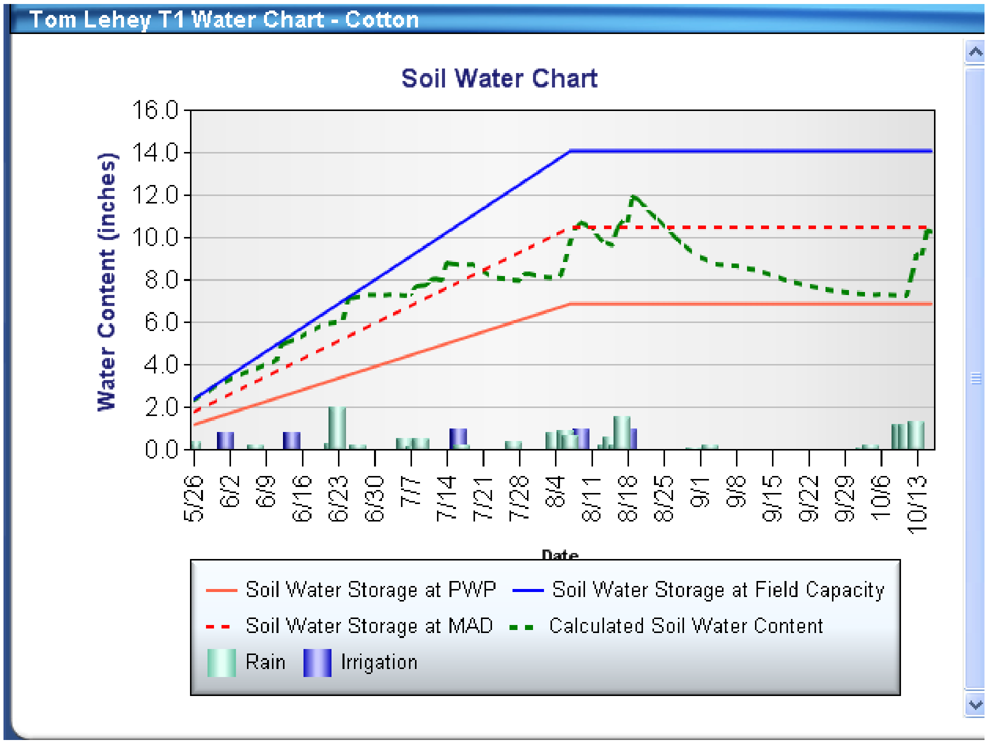

Fig. 1 showing soil water chart for T1 treatment with irrigation and rainfall events.

Treatment T2 was set for two irrigation of same depth of application as T1 each time and the timings were set for July 10 and August 1. However, as mentioned above for treatment T1, the treatment T2 also received pre and post irrigation amounting to 2.4” inches prior to treatment differential application. The first differential application was provided on June 12 followed by one application on July 14. Total irrigation application amounted to 5” inches (Fig. 2). Treatment T3 was set for no irrigation during the growing season except for what was applied to the field as pre-plant and post seeding for germination. Gypsum blocks were placed at one foot depth interval to a depth of four feet to monitor soil water status.

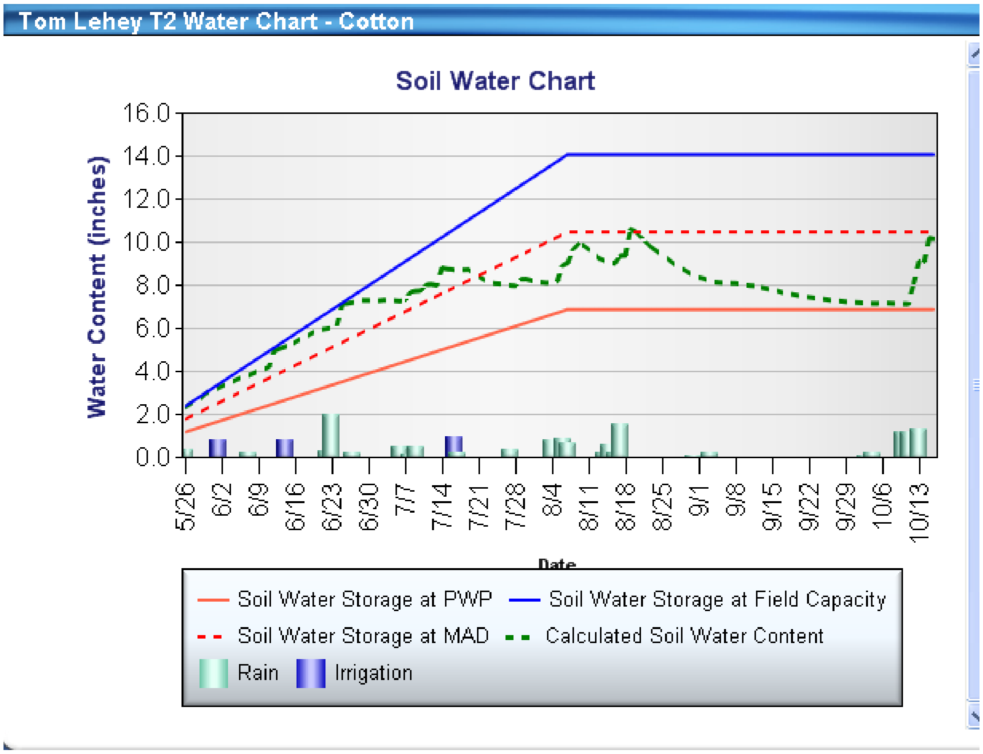

Fig. 2 showing soil water chart for T2 treatment with irrigation and rainfall events

Paymaster 2141, a stripper cotton variety, was planted on May 19, 2008. Plants started to emerge by May 26, 2008. Cotton was harvested on October 28, 2008 by hand to record yield. This was done after the freeze on October 23, 2008, when all mature bolls were open.

Weather data from Garden City experiment station was used for ET data and to calculate cotton growing degree days. Alfalfa based reference ET was used in KanSched irrigation scheduling software to obtain crop ET for cotton under different irrigation treatments.

Results and Discussion**:** One year study results for 2008 indicate that cotton grown in Kansas for a growing period of 140 days used about 16 inches of water as crop ET (Fig. 3); out of this amount 7” inches were provided by irrigation and 8.8 inches were provided by effective rainfall. Seasonal ET of 14.22” inches for treatment T2 was made up from 5” inches of irrigation, 8.8” inches from effective, and less than one half of an inch from soil water. T3 received only pre and post seeding watering amounting to 2.4” inches. Soil water use as shown in figure 3 is based on 100 percent application efficiency of irrigation. At 85 percent application efficiency of water, which is more likely for a center pivot irrigation system the amount of soil water use will probably be a little higher than shown.

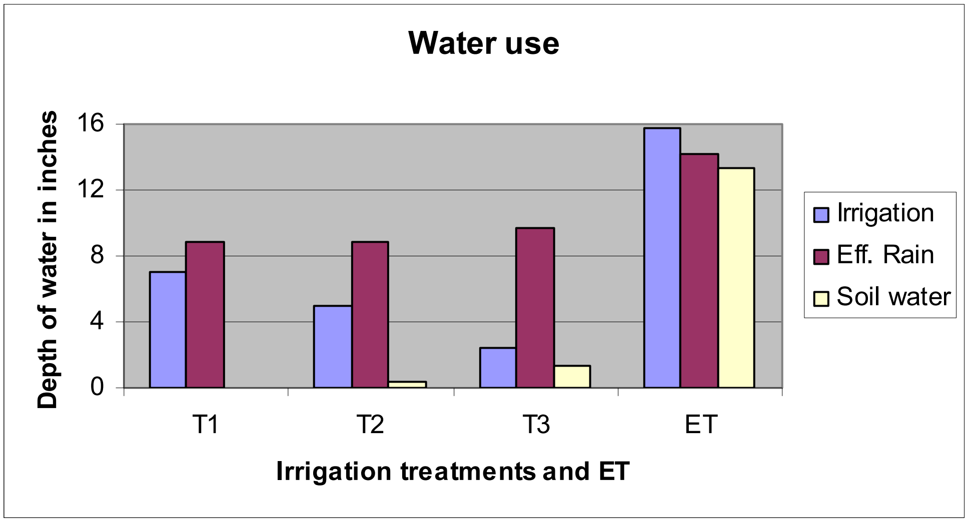

Figure 3 showing seasonal water uses by cotton crop of 2008 in southwest Kansas.

Cotton yield in bales per acre is shown in figure 4. Cotton yield for all three replications were higher for irrigation treatment of 5” inches at an average yield of 2.52 bales per acre. An ET difference of less than an inch between the treatments T2 and T3 has made a yield difference of 400 lbs. per acre. The timing of irrigation to remove water stress is important for cotton crop. It is also critical to avoid high soil water condition for cotton quality and yield.

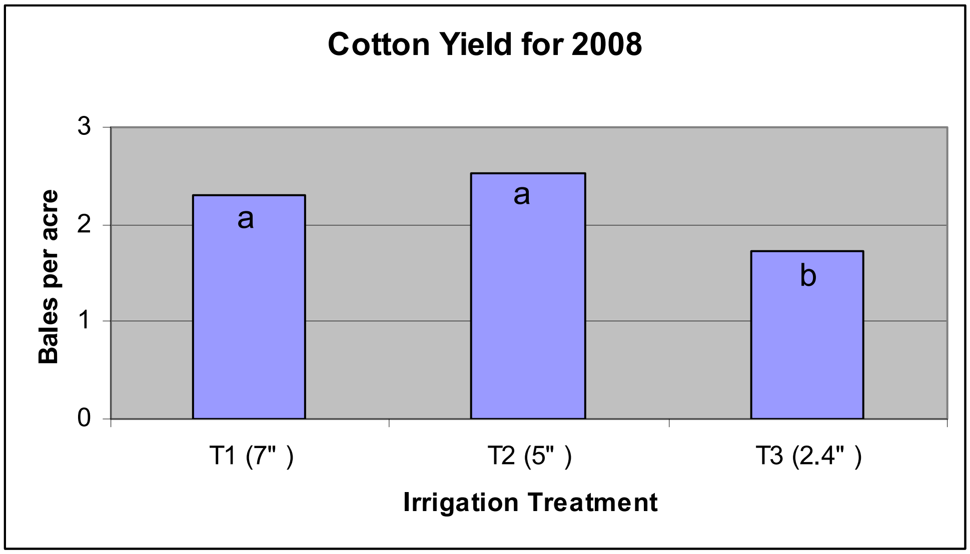

Figure 4 showing cotton yield for different irrigation treatment in 2008.

The harvested samples were sent out to USDA cotton classing office in Abilene, TX, for classification. The salient results are presented in table 1.

Table 1 showing cotton classing results.

Treatment	Color	Mike	Length	Strength
T1	24.3	2.80	1.14	27.20
T2	27.7	2.87	1.13	27.57
T3	31	2.97	1.10	27.23

It appears that the color and mike are inversly related to increased irrigation contributing to prolonged growth. This is probably due to having some late maturing bolls contributing to the production. The length of staple appears to improve with irrigation, but strength of fiber may be sensitive to balanced water management.

The gypsum block readings showing soil water extraction according to gypsum block readings for T1 and T3 are shown in Figure 5-6.

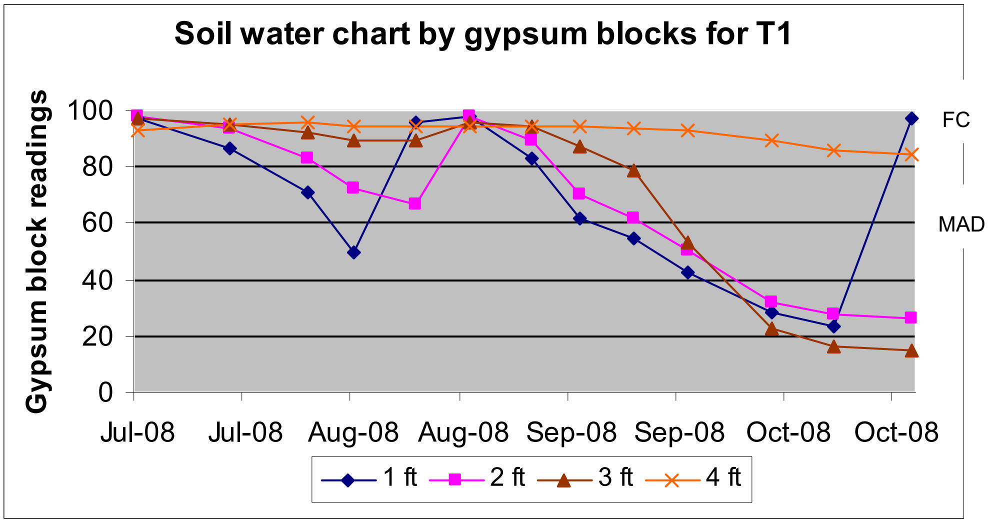

Fig. 5 shows soil water chart according to readings obtained by gypsum blocks.

The soil water status corresponds to what was observed in soil water charts developed by KanSched irrigation scheduling software. The soil water increased back to about field capacity (FC), after a rainfall of 2.6” inches that was spread over three days from August 17 to 19, 2008. Soil water status fell to management allowable depletion level (MAD at gypsum block reading of 60) for T1 treatment by the end of the first week of September. However, no further irrigation was provided to encourage plants to go for life cycle completion.

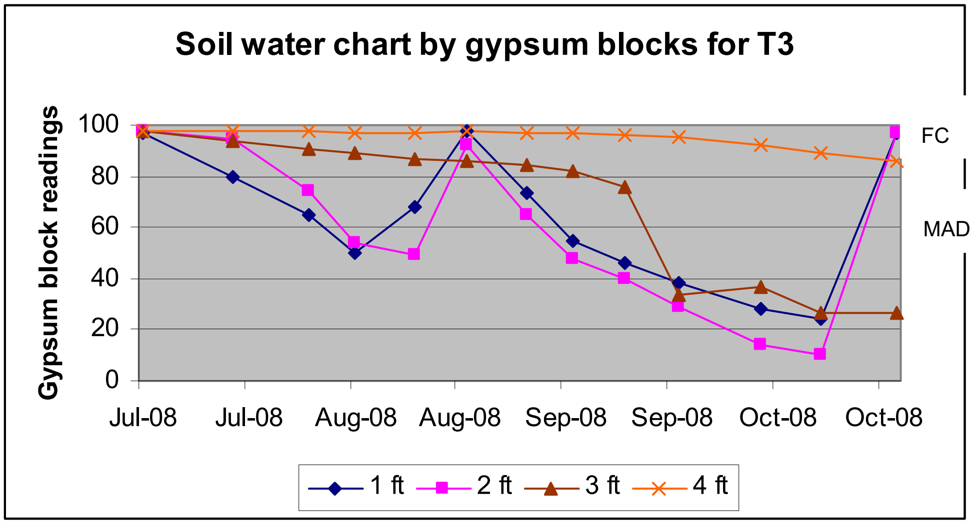

Fig. 6 shows soil water chart from readings obtained by gypsum blocks.

In figure 6 it is visible that the soil water status for first two feet of soil profile, where the roots were most active in early season fell below management allowable depletion by first week of August, and stayed that way until 2.6” inches of rain of third week of August.

Concluding Remarks:

The results presented are from one year study only. The crop of 2009 was completely destroyed by hail storm. The study needs to be repeated for making any conclusive remark. However, it is evident that in a thermally limited area like Kansas, it is critical to manage water for optimum maturity. The yield of cotton may also be limited due to limited growing season and cotton GDD (growing degree days) needed for full maturity of a crop. The cotton GDD from May 26 to October 10 was 1,690 units only and no further increase occurred until freeze on October 23, 2008.

Acknowledgements

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Summary of Twenty Years of Kansas SDI Research

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Abstract. *This paper will summarize research efforts with subsurface drip irrigation in Kansas that have occurred during the period 1989 through 2009. Special emphasis will be made on brief summaries of the different types of research that have been conducted including water and nutrient management for the principal crops of the region, SDI design parameters and system longevity and economics. Annual system performance evaluations have shown that dripline flowrates are within 5% of their original values. Economic analysis shows that systems with such longevity can be cost competitive even for the lower-valued commodity crops grown in the region.*

Keywords. microirrigation, irrigation design, irrigation management, drip irrigation, Great Plains.

Introduction and Brief History

Subsurface drip irrigation (SDI) technologies have been a part of irrigated agriculture since the 1960s, but have advanced at a more rapid pace during the last 20 years (Camp et al. 2000). In the summer of 1988, K-State Research and Extension issued an in-house request for proposals for new directions in research activity. A proposal entitled Sustaining Irrigated Agriculture in Kansas with Drip Irrigation was submitted by irrigation engineers Freddie Lamm, Harry Manges and Dan Rogers and agricultural economist Mark Nelson. This project led by principal investigator Freddie Lamm, KSU Northwest Research-Extension Center (NWREC), Colby, was funded for the total sum of $89,260. This project financed the initial development of the NWREC SDI system that was expressly designed for research. In March of 1989, the first driplines were installed on a 3 acre study site which has 23 separately controlled plots. This site has been in continuous use in SDI corn production since that time, being initially used for a 3-year study of SDI water requirements for corn. In addition, it is considered to be a benchmark area that is also being monitored annually for system performance to determine SDI longevity. In the summer of 1989, an additional 3 acres was developed to determine the optimum dripline spacing for corn production. A small dripline spacing study site was also developed at the KSU Southwest Research-Extension Center (SWREC) at Garden City in the spring of 1989.

In the summer of 1989, further funding was obtained through a special grant from the US Department of Agriculture (USDA). This funding led to expansion of the NWREC SDI research site to a total of 13 acres and 121 different research plots. This same funding provided for a 10 acre SDI research site at Holcomb, Kansas administered by the SWREC. By June of 1990, K-State Research and Extension had established 10 ha of SDI research facilities and nearly 220 separately controlled plot areas.

Over the course of the past 20 years, additional significant funding has been obtained to conduct SDI research from the USDA, the Kansas Water Resources Research Institute, special funding from the Kansas legislature, the Kansas Corn Commission, Pioneer Hi-Bred Inc., and the Mazzei Injector Corporation. Funding provided by the Kansas legislature through the Western Kansas Irrigation Research Project (WKIRP) allowed for the expansion of the NWREC site by an additional 1 acres and 46 additional research plots in 1999. An additional 22 plots were added in 2000 to examine swine wastewater use through SDI and 12 plots were added in 2005 to examine emitter spacing. Three research block areas originally used in a 1989 dripline spacing study have been refurbished with new 5 ft spaced driplines to examine alfalfa production and emitter flowrate effects on soil water redistribution. The NWREC SDI research site comprising 19 acres and 201 different research plots is the largest facility devoted expressly to small-plot row crop research in the Great Plains and is probably one of the largest such facilities in the world.

Since its beginning in 1989, K-State SDI research has had three purposes: 1) to enhance water conservation; 2) to protect water quality, and 3) to develop appropriate SDI technologies for Great Plains conditions. The vast majority of the research studies have been conducted with field corn because it is the primary irrigated crop in the Central Great Plains. Although field corn has a relatively high water productivity (grain yield/water use), it generally requires a large amount of irrigation because of its long growing season and its sensitivity to water stress over a great portion of the growing period. Of the typical commodity-type field crops grown in the Central Great Plains, only alfalfa and similar forages would require more irrigation than field corn. Any significant effort to reduce the overdraft of the Ogallala aquifer, the primary water source in the Central Great Plains, must address the issue of irrigation water use by field corn.

Additional crops that have been studied at the NWREC SDI site are soybean, sunflower, grain sorghum, alfalfa and demonstration trials of melons and vegetables.

General Study Procedures

This report summarizes several studies conducted at the KSU Northwest and Southwest Research-Extension Centers at Colby and Garden City, Kansas, respectively. A complete discussion of all the employed procedures lies beyond the scope of this paper. For further information about the procedures for a particular study the reader is referred to the accompanying reference papers when so listed. These procedures apply to all studies unless otherwise stated.

The two study sites were located on deep, well-drained, loessial silt loam soils. These medium-textured soils, typical of many western Kansas soils, hold approximately 18.9 inches of plant available soil water in the 8 ft profile at field capacity. Study areas were nearly level with land slope less than 0.5% at Colby and 0.15% at Garden City. The climate is semi-arid, with an average annual precipitation of 18 inches. Daily climatic data used in the studies were obtained from weather stations operated at each of the Centers.

Most of the studies have utilized SDI systems installed in 1989-90 (Lamm et al., 1990). The systems have dual-chamber drip tape installed at a depth of approximately 16 to 18 inches with a 60-inch spacing between dripline laterals. Emitter spacing was 12 inches and the dripline flowrate was 0.25 gpm/100 ft. The corn was planted so each dripline lateral is centered between two corn rows (Fig. 1).

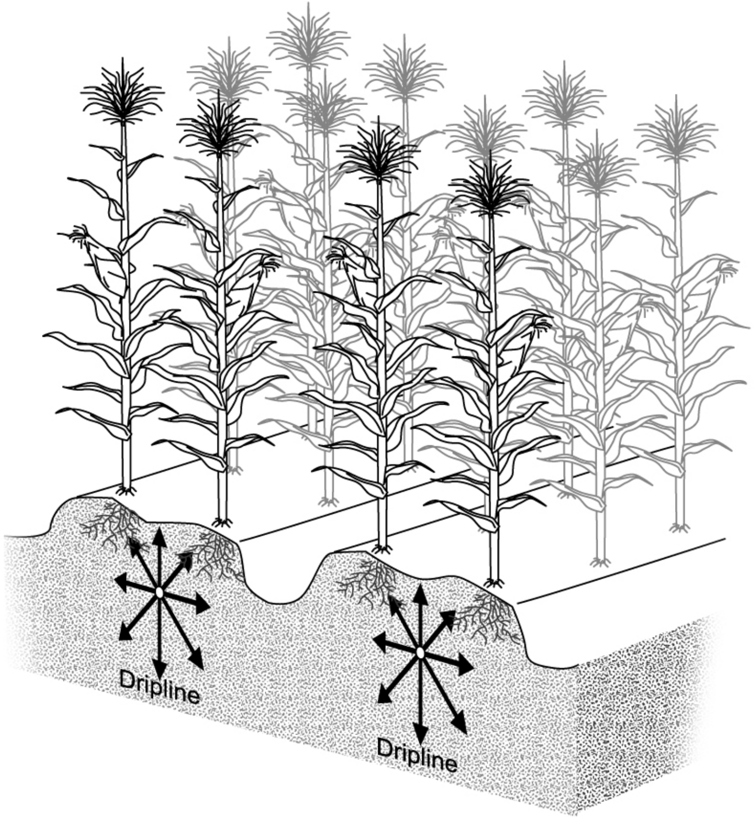

Figure 1. Physical arrangement of the subsurface dripline in relation to the corn rows.

A modified ridge-till system was used in corn production with two corn rows, 30 inches apart, grown on a 60 inch wide bed. Flat planting was used for the dripline spacing studies conducted at both locations. In these dripline spacing studies, it was not practical to match bed spacing to dripline spacing with the available tillage and harvesting equipment. Additionally at Garden City, corn rows were planted perpendicular to the driplines in the dripline spacing study. All corn was grown with conventional production practices for each location. Wheel traffic was confined to the furrows.

Reference evapotranspiration and actual evapotranspiration (AET) were calculated using a modified Penman combination equation similar to the procedures outlined by Kincaid and Heermann (1974). The specifics of the calculations are fully described by Lamm et al. (1995).

Irrigation was scheduled using a water budget to calculate the root zone depletion with precipitation and irrigation water amounts as deposits and calculated daily corn water use (AET) as a withdrawal. If the root-zone depletion became negative, it was reset to zero. Root zone depletion was assumed to be zero at crop emergence. Irrigation was metered separately onto each plot. Soil water amounts were monitored weekly in each plot with a neutron probe in 12 inch increments to a depth of 8 ft.

Results and Discussion

Water Requirement and Irrigation Capacity Studies

Research studies were conducted at Colby from 1989-1991 to determine the water requirement of subsurface drip-irrigated corn. Careful management of SDI systems reduced net irrigation needs by nearly 25%, while still maintaining top yields of 200 bu/a (Lamm et. al., 1995). The 25% reduction in irrigation needs potentially translates into 35-55% savings when compared to sprinkler and furrow irrigation systems which typically are operating at 85 and 65% application efficiency. Corn yields at Colby were linearly related to calculated crop water use (Figure 2), producing 19.6 bu/acre of grain for each inch of water used above a threshold of 12.9 inches (Lamm et al., 1995). The relationship between corn yields and irrigation is curvilinear (Figure 2.) primarily because of greater drainage for the heavier irrigation amounts (Figure 3).

SDI technology can make significant improvements in water productivity through better management of the water balance components. The 25% reduction in net irrigation needs is primarily associated with the reduction in in-season drainage, elimination of irrigation runoff and reduction in soil evaporation, all non-beneficial components of the water balance. Additionally, drier surface soils allow for increased infiltration of occasional precipitation events.

In a later study (1996-2001), corn was grown under 6 different SDI capacities (0, 0.10, 0.13, 0.17, 0.20 and 0.25 inches/day) and 4 different plant densities (33,100, 29,900, 26,800, and 23,700 plants/acre). Daily SDI application of even small amounts of water (0.10 inches) doubled corn grain yields from 92 to 202 bu/acre in extremely dry 2000 and 2001. Results suggested an irrigation capacity of 0.17 inches/day might be adequate SDI capacity when planning new systems in this region on deep silt loam soils (Lamm and Trooien, 2001). It was concluded that small daily amounts of water can be beneficial on these deep silt loam soils in establishing the number of sinks (kernels) for the accumulation of grain. The final kernel mass is established by grain filling conditions between the reproductive period and physiological maturity (last 50-60 days of crop season). Thus, the extent of soil water depletion during this period will have a large effect on final kernel mass and ultimately, corn grain yield. Increasing plant density from 22,500 to 34,500 plants/acre generally increased corn grain yields, particularly in good corn production years. There was very little yield penalty for increased plant density even when irrigation was severely limited or eliminated.

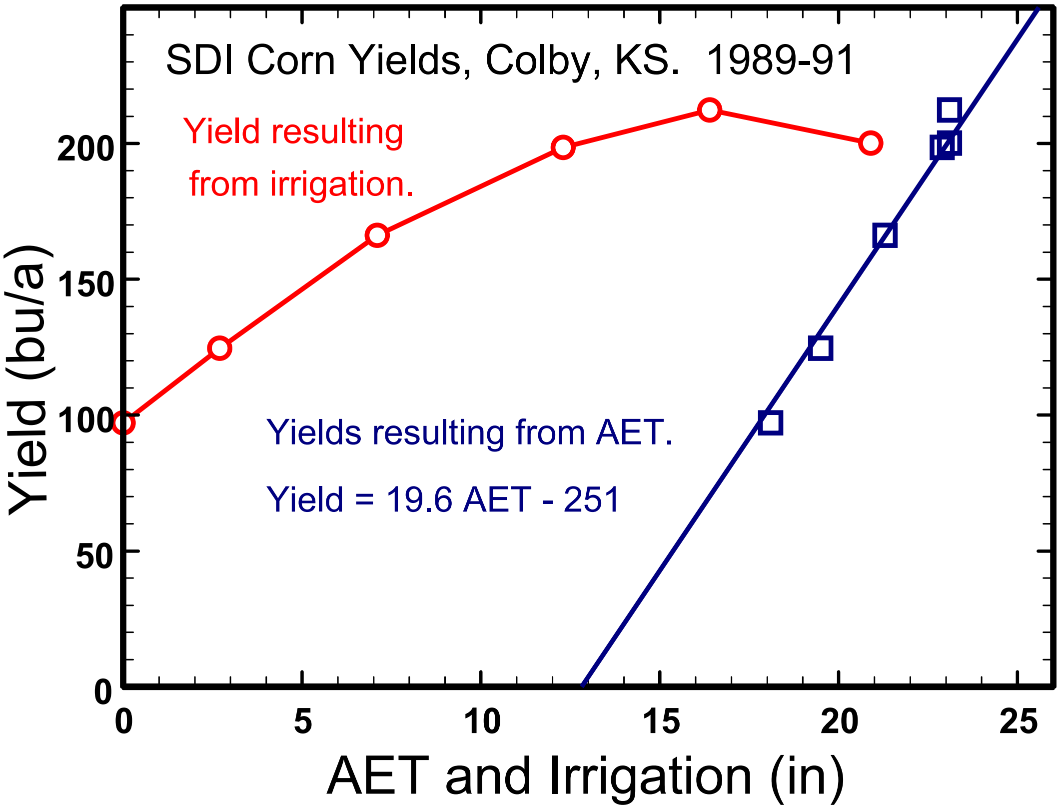

Figure 2. Corn yield as related to irrigation and calculated evapotranspiration (AET) in a SDI water requirement study, Colby, Kansas, 1989-1991.

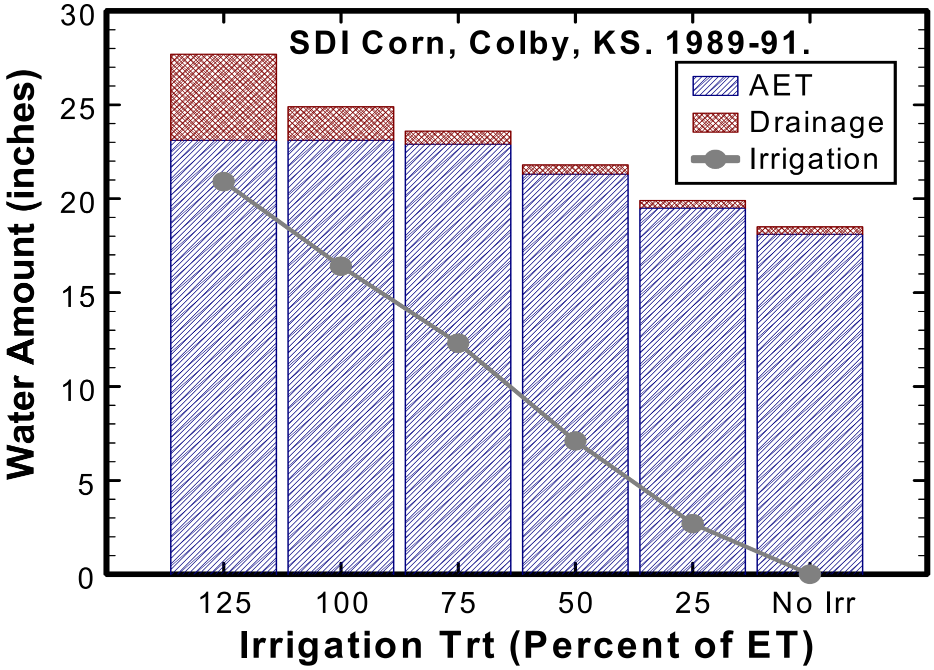

Figure 3. Calculated evapotranspiration (AET) and seasonal drainage as related to irrigation treatment in a SDI water requirement study, Colby, Kansas, 1989-1991.

The results from four SDI studies on corn water use were summarized by Lamm, 2005. Relative corn yield reached a plateau region at about 80% of full irrigation and continued to remain at that level to about 130% of full irrigation (Figure 4). Yield variation as calculated from the regression equation for this plateau region is less than 5% and would not be considered significantly different. The similarity of results for all four studies is encouraging because the later studies included the effect of the four extreme drought years of 2000 through 2003.

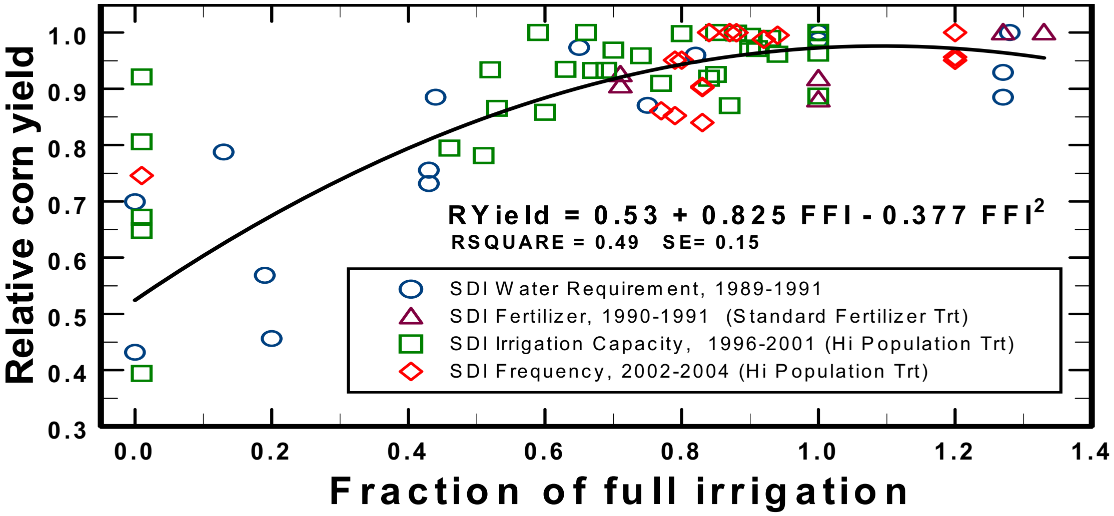

Figure 4. Relative corn grain yield for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

An examination of water productivity (WP) for the same four studies indicates that water productivity plateaus for levels of full irrigation ranging from 61% to 109% with less than 5% variation in WP (Figure 5). The highest WP occurs at an irrigation level of approximately 82% of full irrigation. This value agrees with results summarized by Howell, (2001) for multiple types of irrigation systems. The greatest WP (82% of full irrigation) also occurred in the plateau region of greatest corn yield (80 to 130% of full irrigation). This suggests that both water- and economically-efficient production can be obtained with SDI levels of approximately 80% of full irrigation across a wide range of weather conditions on these soils in this region.

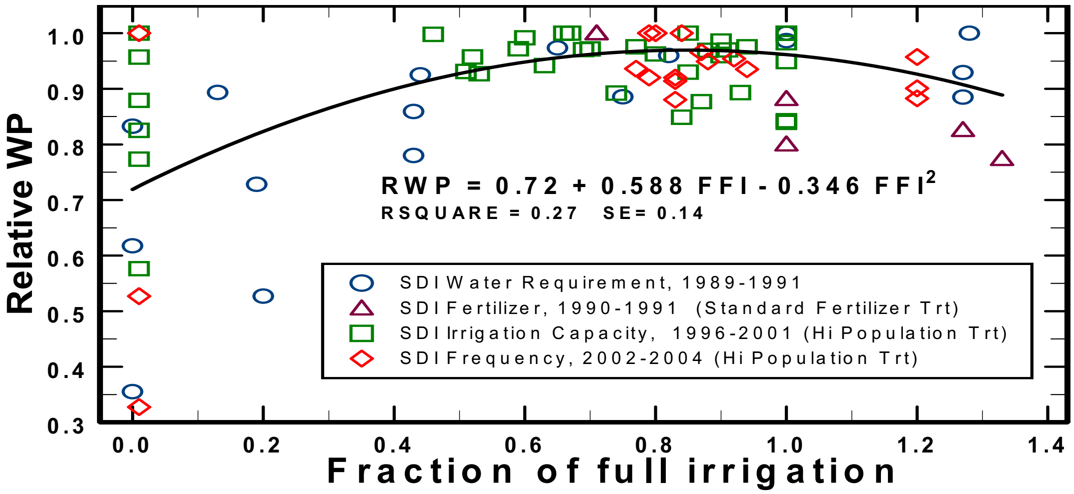

Figure 5. Relative water use productivity (WP) of corn for a given SDI research study and year as related to the fraction of full irrigation, Colby, Kansas.

SDI Frequency

Typically, a smaller volume of soil is wetted with SDI as compared to other types of irrigation systems and as a result, crop rooting may be limited. Crops may benefit from frequent irrigation under this condition. However, in a study conducted at the KSU Southwest Research-Extension Center in Garden City, Kansas, corn yields were excellent (190 to 200 bu/acre) regardless of whether a frequency of 1, 3, 5, or 7 days was used for the SDI events (Caldwell et al., 1994). Higher irrigation water use efficiencies were obtained with the longer 7-day frequency because of improved storage of in-season precipitation and because of reduced drainage below the rootzone. The results indicate there is little need to perform frequent SDI events for fully-irrigated corn on the deep silt loam soils of western Kansas.

These results agree with a literature review of SDI (Camp, 1998) that indicated that SDI frequency is often only critical for shallow rooted crops on shallow or sandy soils. An additional study conducted in the U.S. Southern Great Plains indicated that SDI frequencies had little or no effect on corn yields provided soil water was managed within acceptable stress ranges (Howell et al., 1997).

In a 2002-2004 study at Colby, Kansas, four irrigation frequencies at a limited irrigation capacity were compared against fully irrigated and non-irrigated treatments (Lamm and Aiken, 2005). The hypothesis was that under limited irrigation, higher frequency with SDI might be beneficial during grain filling and the latter portion of the season as soil water reserves become depleted. The four irrigation frequencies were 0.15 in/day, 0.45 in/3 days, 0.75/5 days and 1.05/7days which are equivalent but limited capacities. As a point of reference, a 0.25 in/day irrigation capacity will match full irrigation needs for sprinkler irrigated corn in this region in most years. The fully irrigated treatment was limited to 0.30 in/day. The non-irrigated treatment only received 0.10 inches in a single irrigation to facilitate nitrogen fertigation for those plots. However, all 6 treatments were irrigated each year in the dormant season to replenish the soil water in the profile. Corn yields were high in all three years for all irrigated treatments (Figure 6.)

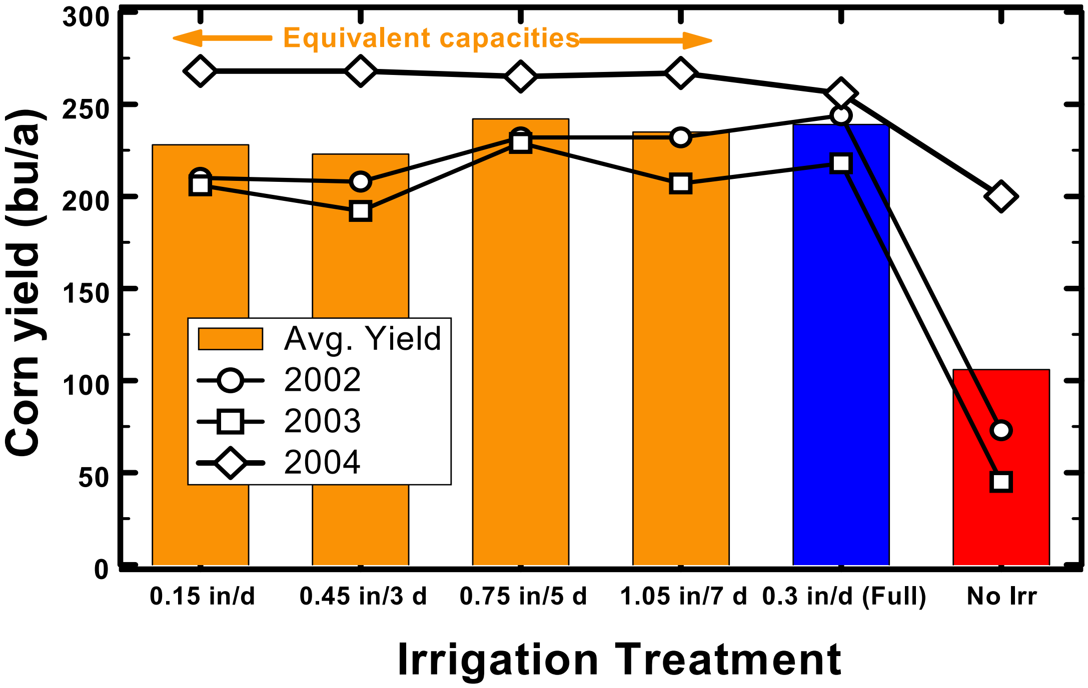

Figure 6. Corn grain yields as affected by irrigation treatment in a study examining SDI frequency under limited irrigation, Colby, Kansas, 2002 to 2004.

Only in 2002 did irrigation frequency significantly affect yields and the effect was the opposite of the hypothesis. In the extreme drought year of 2002, the less frequent irrigation events with their larger irrigation amounts (0.75 in/5 days and 1.05 in/7 days) resulted in yields approximately 10 to 20 bu/acre higher. The yield component most greatly affected in 2002 was the kernels/ear and was 30-40 kernels/ear higher for the less frequent events. It is suspected that the larger irrigation amounts for these less frequent events sent an early-season signal to the corn plant to set more potential kernels. Much of the potential kernel set occurs before the ninth leaf stage (corn approximately 2 to 3 ft tall), but there can be some kernel abortion as late as two weeks after pollination. The results suggest that irrigation frequencies from daily to weekly should not have much effect on corn yields in most years.

Optimal Dripline Spacing

Increasing the spacing of dripline laterals would be one of the most important factors in reducing the high investment costs of SDI. Soil type, dripline installation depth, crop type and the reliability and amount of in-season precipitation are major factors that determine the maximum dripline spacing.

Two studies have been conducted in semi-arid western Kansas to determine the optimum dripline spacing (installed at a depth of 16 to 18 inches) for corn production on deep, silt-loam soils (Spurgeon, et al., 1991; Manges et al., 1995; Darusman et al., 1997; Lamm et al., 1997a). The first study at the KSU Southwest Research-Extension Center at Garden City, Kansas evaluated 4 dripline spacings (2.5, 5, 7.5, and 10 ft) with corn planted in 30-inch spaced rows perpendicular to the dripline lateral. The other study at the KSU Northwest Research-Extension Center at Colby, Kansas evaluated 3 spacings (5, 7.5 and 10 ft) with corn planted in 30-inch spaced rows parallel to the driplines. Average yields for corresponding treatments were similar between sites even though row orientation was different (Table 1).

Table 1. Corn yields obtained with various dripline spacing treatments under full and reduced irrigation at Garden City and Colby, Kansas, 1989-91.

Spacing treatment	Irrigation treatment	Dripline ratio in relation to 5-ft. trt.	Corn yield (bu/a) Garden City 1989-91	Colby 1990-91
2.5 ft.	Full irrigation	2.00	230	----
5.0 ft	Full irrigation	1.00	218	216
7.5 ft	Full Irrigation	0.67	208	204
7.5 ft	Reduced irrigation (67%)	0.37	----	173
10.0 ft	Full irrigation	0.50	194	194
10.0 ft	Reduced irrigation (50%)	0.50	----	149

The highest average yield was obtained by the 2.5-ft dripline spacing at Garden City, Kansas. However, the requirement of twice as much dripline (dripline ratio, 2.00) would be uneconomical for corn production as compared to the standard 5-ft dripline spacing. The results, when incorporated into an economic model, showed an advantage for the wider dripline spacings (7.5 and 10ft in some higher rainfall years. However, the standard 5 ft dripline spacing was best when averaged over all years for both sites. When subsurface driplines are centered between alternate pairs of 30-inch spaced corn rows, each corn row is within 15 inches of the nearest dripline (Figure 1.)

Wider dripline spacings will not consistently (year-to-year) or uniformly (row-to-row) supply crop water needs. In 1990 at Colby, yields for the 5 ft and 7.5 ft dripline spacings were equal when full irrigation was applied, partially because soil water reserves were high at planting. In 1991, following a dry winter, yields for the wider 7.5 ft dripline spacing were reduced by 25 bu/acre (Lamm et al., 1997a). Similar results were reported by Spurgeon et al. (1991) at Garden City. The studies at Colby also sought to resolve whether equivalent amounts of water should be applied to the wider dripline spacings or whether irrigation should be reduced in relation to the dripline ratio. Yields were always lower for the corn rows furthest from the dripline in the wider dripline spacings regardless of which irrigation scheme was used (Figure 7). However in 1991, there was complete crop failure in the corn rows furthest from the dripline when irrigation was reduced in relation to the dripline ratio. Full irrigation on the wider dripline spacings at Colby resulted in excessive deep percolation (Darusman et al., 1997) and reduced overall water productivity (Lamm et al., 1997a). Soils having a restrictive clay layer below the dripline installation depth might allow a wider spacing without affecting crop yield. Wider spacings may also be allowable in areas of increased precipitation as the dependency of the crop on irrigation is decreased (Powell and Wright, 1993).

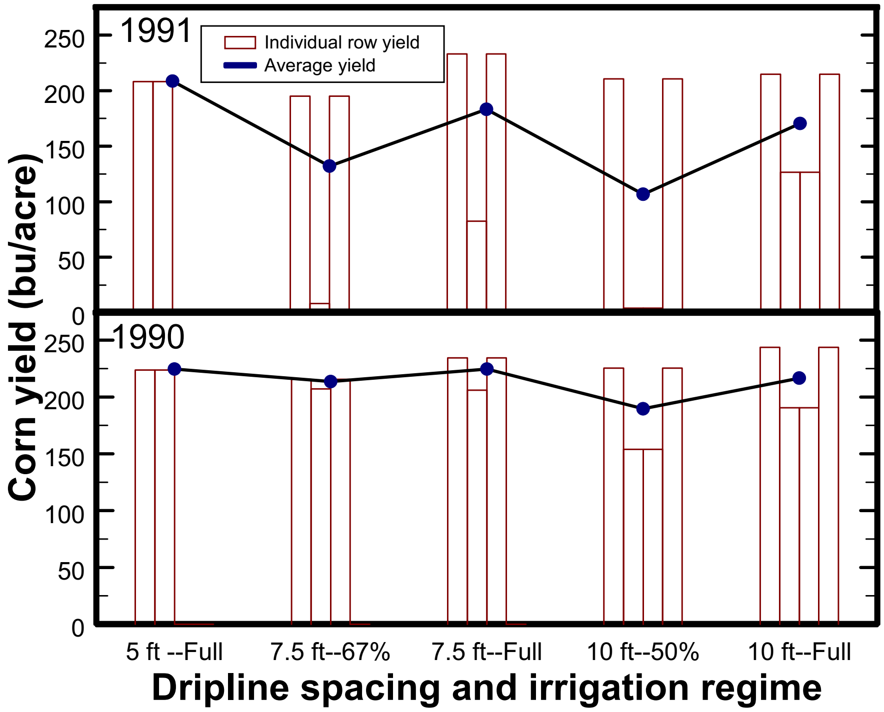

Figure 7. Corn yield distribution as affected by dripline spacing and irrigation regime, Colby, Kansas, 1990-1991. Note: Individual row yields are mirrored about a centerline half way between two adjacent driplines for display purposes.

One of the inherent advantages of a SDI system is the ability to irrigate only a fraction of the crop root zone. Careful attention to proper dripline spacing is, therefore, a key factor in conserving water and protecting water quality. These research studies at Colby and Garden City, Kansas determined that driplines spaced 5 ft apart are most economical for corn grown in rows spaced 30 inches apart at least on the deep silt loam soils of the region. However, different soil types, such as sands, or different crops with less extensive root systems might require closer dripline spacing.

Dripline Depth Study

In some areas, SDI has not been readily accepted because of problems with root intrusion, emitter clogging and lack of visual indicators of the wetting pattern. In high value crops, these indeed can be valid reasons to avoid SDI. However, in the Central Great Plains, with typically relatively low value commodity crops such as corn, only long term SDI systems where installation and investment costs can be amortized over many years, have any realistic chance of being economically justified. Kansas irrigators are beginning to try SDI on their own and there has been a lack of research-based information on appropriate depth for driplines. Camp (1998) reviewed a number of SDI studies concerning depth of installation and concluded the results are often region specific and optimized for a particular crop. Five dripline depths (8, 12, 16, 20 and 24 inches) were evaluated at Colby, Kansas for corn production and SDI system integrity and longevity (Lamm and Trooien, 2005). System longevity was evaluated by monitoring individual flowrates and pressures at the end of each cropping season to estimate system degradation (clogging) with time. There was no appreciable or consistent effect on corn grain yields during the period 1999-2002 (Figure 8.).

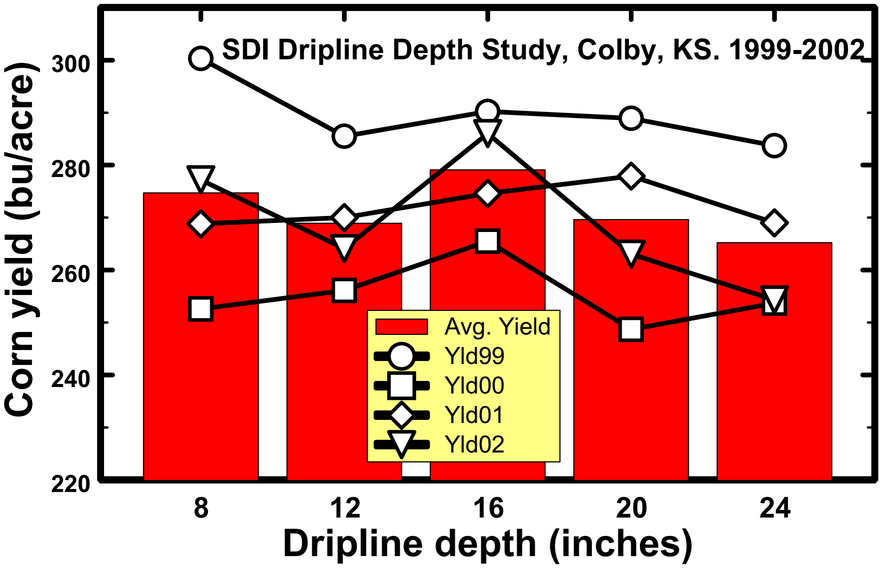

Figure 8. Corn grain yields as affected by dripline depth, 1999-2002, Colby, Kansas.

The study area has not been used to examine the effects of dripline depth on germination in the spring, but damp surface soils were sometimes observed for the 8 and 12 inch dripline depths during the irrigation season, but not for the deeper depths. There was a tendency to have slightly more late season grasses for the shallower 8 and 12 inch depths, but the level of grass competition with the corn is not intense. The dripline depth study was managed with the modified ridge-till system (5-ft bed) as shown in Figure 1. Cultivation for weeds in early summer has been routinely practiced and there were no instances of tillage tool damage to the shallow 8 inch depth driplines.

Similar dripline depth studies were conducted for soybean (2005 and 2007), grain sorghum (2006 and 2008) and sunflower (2004 and 2007). There were no significant differences in yields for any of the crops in any year as affected by dripline depth (Table 2.)

Table 2. Crop yield of soybean, grain sorghum and sunflower as affected by dripline depth, KSU Northwest Research-Extension Center, Colby Kansas, 2003-2008.

Dripline depth inches	**Soybean yield bu/acre**			**Grain Sorghum bu/acre**			**Sunflower lbs/acre**		
	2005	**2007**	**Mean**	**2006**	**2008**	**Mean**	**2004**	**2007**	**Mean**
8	80	76	78	166	153	159	3128	3487	3307
12	82	71	76	159	155	157	2838	3309	3074
16	80	76	78	165	169	167	2941	3580	3261
20	80	74	77	159	157	158	2992	3489	3241
24	78	78	78	155	141	148	2942	3497	3220
Mean	80	75	77	161	155	158	2968	3473	3220
LSD 0.05	NS	NS	-	NS	NS	-	NS	NS	-

Nitrogen Fertilization with SDI

Because properly designed SDI systems have a high degree of uniformity and can apply small frequent irrigation amounts, excellent opportunities exist to better manage nitrogen fertilization with these systems. Injecting small amounts of nitrogen solution into the irrigation water can spoonfeed the crop, while minimizing the pool of nitrogen in the soil that could be available for percolation into the groundwater.

In a study conducted at the KSU Northwest Research-Extension Center at Colby, Kansas from 1990-91, there was no difference in corn grain yields between preplant surface-applied nitrogen and nitrogen injected into the driplines throughout the season. Corn yields averaged 225 to 250 bu/acre for the fully irrigated and fertilized treatments. Water use was increased (P=0.05) in 1991 and for the two year average by injection of N fertilizer with the SDI system. The additional in-season fertigation allowed for healthier and more vigorous plants that were better able to utilize soil water. The results suggest that a large portion of the applied N could be delayed until weekly injections begin with the first irrigation provided there is sufficient residual soil N available for early growth. In both years, nearly all of the residual nitrate nitrogen measured after corn harvest was located in the upper 12 inches of the soil profile for the preplant surface-applied nitrogen treatments, regardless of irrigation level. In contrast, nitrate concentrations increased with increasing levels of nitrogen injected with SDI and migrated deeper in the soil profile with increased irrigation (Lamm et. al., 2001). Nitrogen applied with SDI at a depth of 16 to 18 inches redistributed differently in the soil profile than surface-applied preplant nitrogen banded in the furrow (Figure 9*).* *Since residual soil-nitrogen levels were higher where nitrogen was injected using SDI, it may be possible to obtain similar high corn yields using lower amounts of injected nitrogen.*

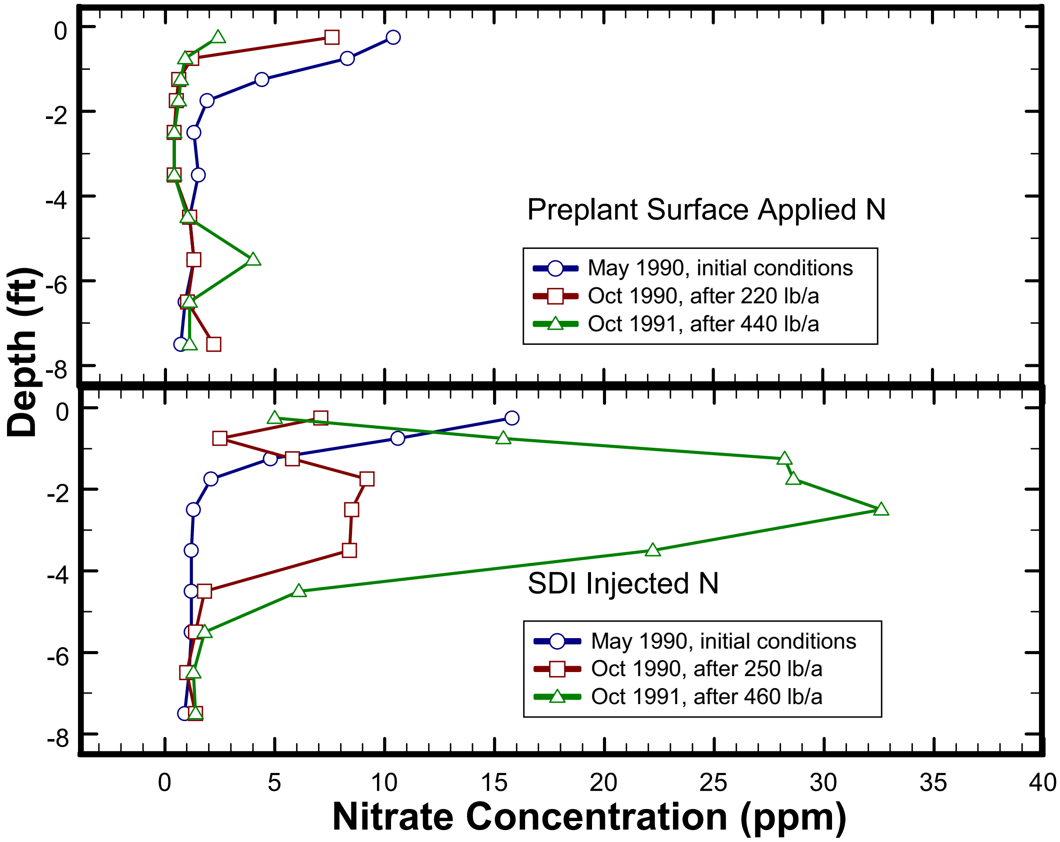

Figure 9. Nitrate concentrations in the soil profile for preplant surface-applied and SDI injected nitrogen treatments, Colby, Kansas, 1990-91. Data is for selected nitrogen fertilizer rate treatments with full irrigation (100% of AET).

A follow-up four year study was conducted at the KSU Northwest Research-Extension Center at Colby, Kansas on a deep Keith silt loam soil to develop a Best Management Practice (BMP) for nitrogen fertigation for corn using SDI. Residual ammonium- and nitrate-nitrogen levels in the soil profile, corn yields, apparent nitrogen uptake (ANU) and water productivity (WP) were utilized as criteria for evaluating six different nitrogen fertigation rates, 0, 90, 135, 180, 225, and 270 kg/ha. The final BMP was a nitrogen fertigation level of 180 kg/ha with other non-fertigation applications bringing the total applied nitrogen to approximately 215 kg/ha (Lamm et. al., 2004). The BMP also states that irrigation is to be scheduled and limited to replace approximately 75% of ET. Corn yield, ANU, and WP all plateaued at the same level of total applied nitrogen which corresponded to the 180 kg/ha nitrogen fertigation rate (Figure 10). Average yields for the 180 kg/ha nitrogen fertigation rate was 13.4 Mg/ha. Corn yield to ANU ratio for the 180 kg/ha nitrogen fertigation rate was a high 53:1. The results emphasize that high-yielding corn production also can be efficient in nutrient and water use.

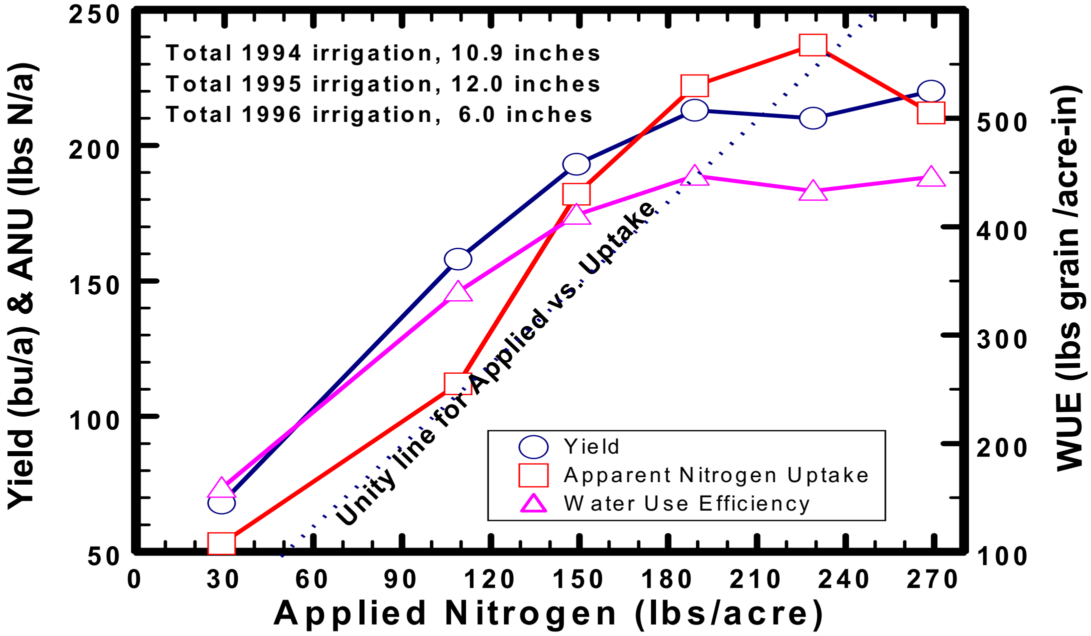

Figure 10. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water productivity as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded fertigation applied nitrogen by 30 lb/acre.

Comparison of SDI and Simulated LEPA Sprinkler Irrigation

A seven-year field study (1998-2004) compared simulated low energy precision application (LEPA) sprinkler irrigation to subsurface drip irrigation (SDI) for field corn production on deep silt loam soils at Colby, Kansas (Lamm, 2004). There was very little difference in average corn grain yields between system type (235 and 233 bu/acre for LEPA and SDI, respectively) across all comparable irrigation capacities (Figure 11). However, LEPA had higher grain yields for 4 extreme drought years (approximately 15 bu/acre) and SDI had higher yields in 3 normal to wetter years (approximately 15 bu/acre).

The difference in system types between years was unanticipated and remains unexplained. In the course of conducting this experiment it became apparent that system type was affecting grain yields particularly in the extreme drought years. Higher LEPA yields were associated with higher kernels/ear as compared to SDI (534 vs. 493 kernels/ear in dry years). Higher SDI yields were associated with higher kernel mass at harvest as compared to LEPA (347 vs. 332 mg/kernel in normal to wetter years). Although the potential number of kernels/ear is determined by hybrid genetics and early growth before anthesis, the actual number of kernels is usually set in a 2-3 week period centering around anthesis. Water and nitrogen availability and hormonal signals are key factors in determining the actual number of kernels/ear. The adjustment of splitting the fertilizer applications to both preplant and inseason in 2002 did not remove the differences in kernels/ear between irrigation system types. Hormonal signals sent by the roots may have been different for the SDI treatments in the drought years because SDI may have had a more limited root system. Seasonal water use was approximately 4% higher with LEPA than SDI and was associated with the period from anthesis to physiological maturity. Further research is being conducted to gain an understanding of the reasons between the shifting of the yield components (kernels/ear and kernel mass) between irrigation systems as climatic conditions vary.

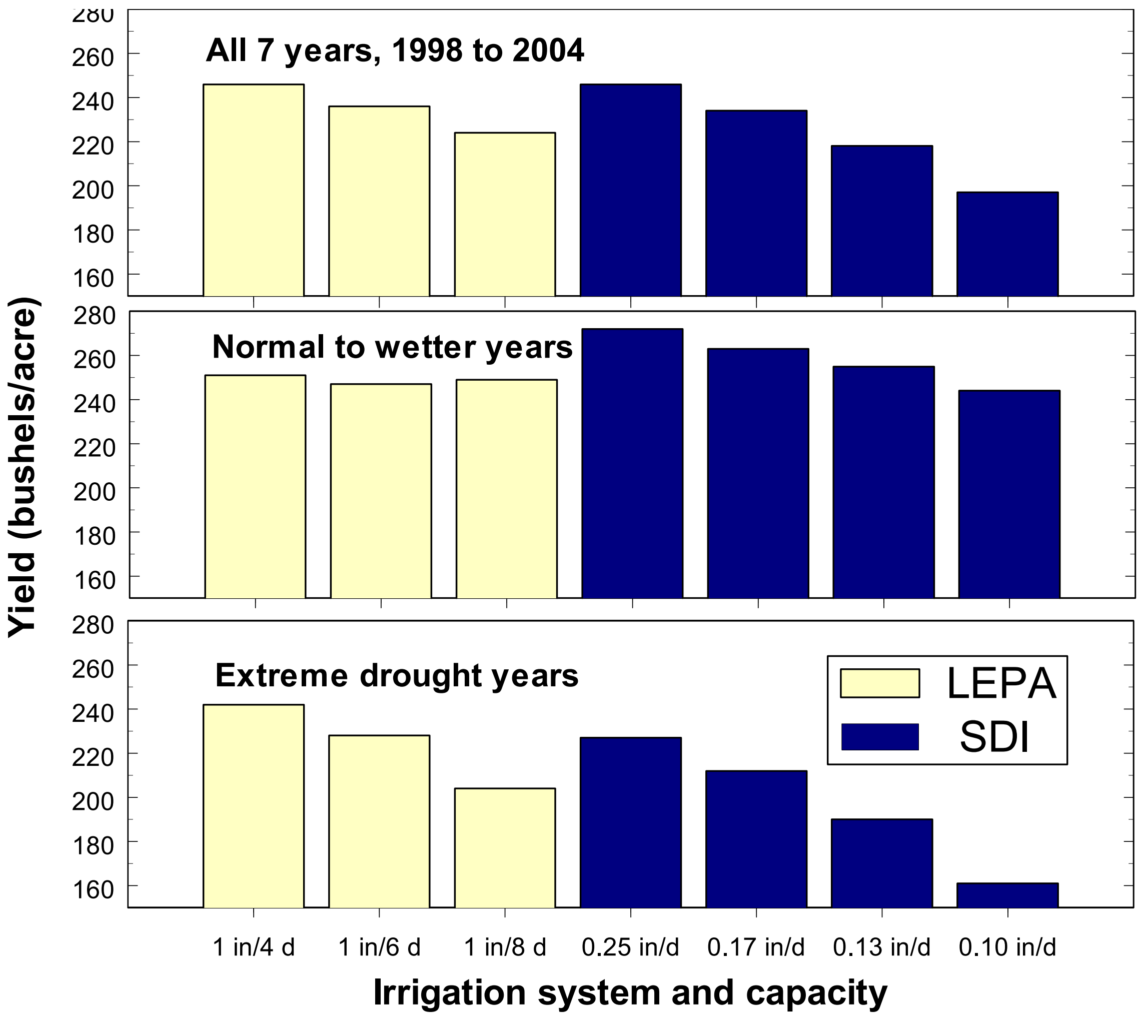

Figure 11. Variation in corn yields across years and weather conditions as affected by irrigation system type and capacity, Colby Kansas.

Additional studies were conducted to compare LEPA sprinkler irrigation to SDI for production of soybeans (2005), grain sorghum (2006 and 2008) and sunflower (2004 and 2007). In these studies, weather-based water-budget irrigation schedules were used to replace ET at replacement levels of 100, 80 and 60% for both types of irrigation system.

There were no significant differences in soybean yield but there was a trend towards SDI having greater yield at deficit irrigation levels and LEPA having greater yield at the full irrigation level (Table 3). Similar statistically non-significant results were obtained for sunflower with a trend towards SDI resulting in greater yields under deficit irrigation (0.6 and 0.8 ET) than LEPA, but LEPA having greater yields at full irrigation in both years. Grain sorghum tended to have greater yields with LEPA than with SDI at all levels of irrigation and was statistically significant in 2008. Further analysis and research is needed to determine the reasons for these results.

Table 3. Crop yield of soybean, grain sorghum and sunflower as affected by irrigation method and irrigation treatment, KSU Northwest Research-Extension Center, Colby Kansas, 2004-2008.

Irrigation method	**Irrigation Treatment**	**Soybean yield bu/a**	**Grain Sorghum bu/a**			**Sunflower yield bu/a**		
		2005	**2006**	**2008**	**Mean**	**2004**	**2007**	**Mean**
SDI	100% ET	73	169	154 b*	161	3098	2824	2961
	80% ET	70	175	144 b	159	3442	3292	3367
	60% ET	70	155	131 c	143	3346	3273	3309
	Mean SDI	71	166	143	155	3295	3130	3212
LEPA	100% ET	75	179	170 a	174	3694	3354	3524
	80% ET	71	180	169 a	175	3285	2929	3107
	60% ET	63	175	160 a	167	3125	2729	2927
	Mean LEPA	69	178	167	172	3368	3004	3186
	LSD 0.05	NS	NS	13	-	NS	NS	-

** Values followed by the same lower case letter are not significantly different at the P=0.05 level.*

Alfalfa Production with SDI

Alfalfa, a forage crop, has high crop water needs and, thus, can benefit from highly efficient irrigation systems such as SDI. In some regions, the water allocation is limited by physical or institutional constraints, so SDI can effectively increase alfalfa production by increasing the crop transpiration while reducing or eliminating soil evaporation. Since alfalfa is such a high-water user and has a very long growing season, irrigation labor requirements with SDI can be reduced relative to less efficient alternative irrigation systems that would require more irrigation events (Hengeller, 1995). A major advantage of SDI for alfalfa is the ability to continue irrigating immediately prior, during, and immediately after the multiple seasonal harvests. Continuation of irrigation reduces the amount of water stress on the alfalfa and thus can increase forage production which is generally linearly related to transpiration.

A study was conducted from 2004 through 2007 to evaluate alfalfa production using an SDI system with an 5-ft dripline spacing and a 20-inch dripline depth on a deep silt loam soil at the KSU Northwest Research-Extension Center at Colby, Kansas. Alfalfa production and quality was evaluated with respect to three irrigation levels (trts. designed to replace 70, 85 and 100% of ETc) and at three perpendicular horizontal distances from the dripline (0, 15 and 30 inches).

There were not large differences in annual yield between irrigation levels but over the course of each season there would tend to be a slight reduction in alfalfa yield with increasing distance from the dripline. This reduction was greater for the 70% ET treatment and resulted in reduced overall annual yields (Figure 12). However, crude protein (a measure of alfalfa quality) and digestibility was greater at the greater distances and reduced ET. This helped compensate for the yield reduction.

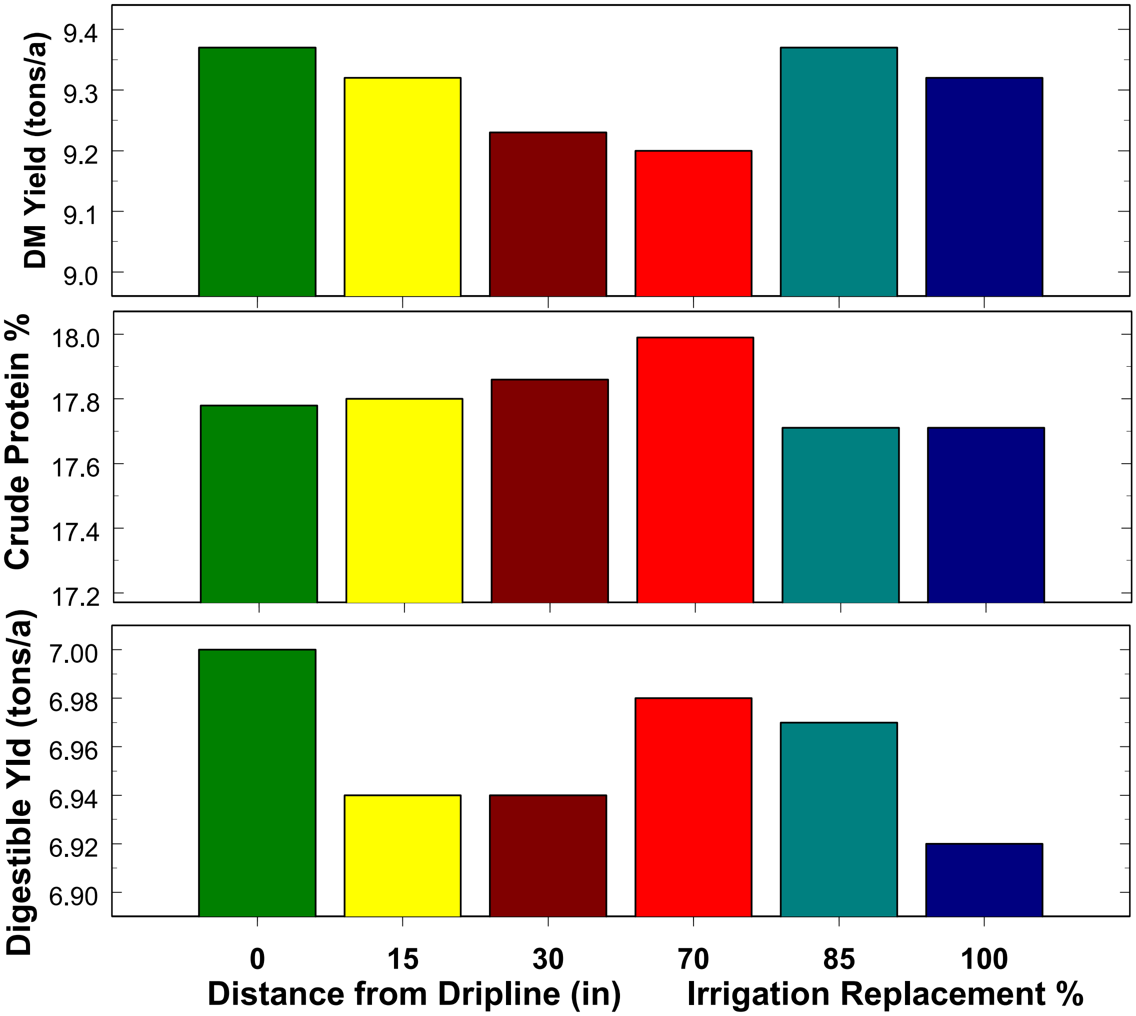

Figure 12. Dry matter yield, percentage crude protein and digestible dry matter yield as affected by perpendicular horizontal distance from dripline and irrigation level, KSU Northwest Research-Extension Center, Colby Kansas. Data is averaged over the years, 2005 through 2007.

Additional data collected from a field demonstration study conducted by K-State indicates that a 40-inch spacing of dripline for alfalfa may recover the additional investment cost. This is more so for the traditional alfalfa growing areas in Kansas which tend to have comparatively light textured soils (Alam et al., 2009).

Application of Livestock Effluent with SDI

Subsurface drip irrigation (SDI) can be successfully used for application of livestock effluent to agricultural fields with careful consideration of design and operational issues. Primary advantages are that exposure of the effluent to volatilization, leaching, runoff into streams, and humans can be reduced while the primary disadvantages are related to system cost and longevity, and the fixed location of the SDI system.

An engineering feasibility study (1998 to 2002, commercial beef feedlot in Gray County, Kansas) conducted by Kansas State University with beef feedlot effluent has indicated that driplines with discharge of 0.4 to 1 gal/hr-emitters can be used successfully with little clogging.

However, the smaller emitter sizes normally used with high quality groundwater in the Central Great Plains may be risky for use with beef feedlot effluent. The discharge of the two smallest emitter sizes, 0.15 and 0.24 gal/hr-emitter decreased approximately 40% and 30%, respectively, during the four seasons, indicating considerable emitter clogging (Figure 13). The three driplines with the highest flow rate emitters (0.4, 0.6, and 0.92 gal/hr-emitters) have had approximately 7, 8, and 13% reductions in flow rate, respectively. Following an aggressive freshwater flushing, acid and chlorine injections in April of 2002, the flowrates of the lowest two emitter sizes (0.15 and 0.24 gal/hr-emitter) were restored to nearly 80 and 97% of their initial flowrates, respectively.

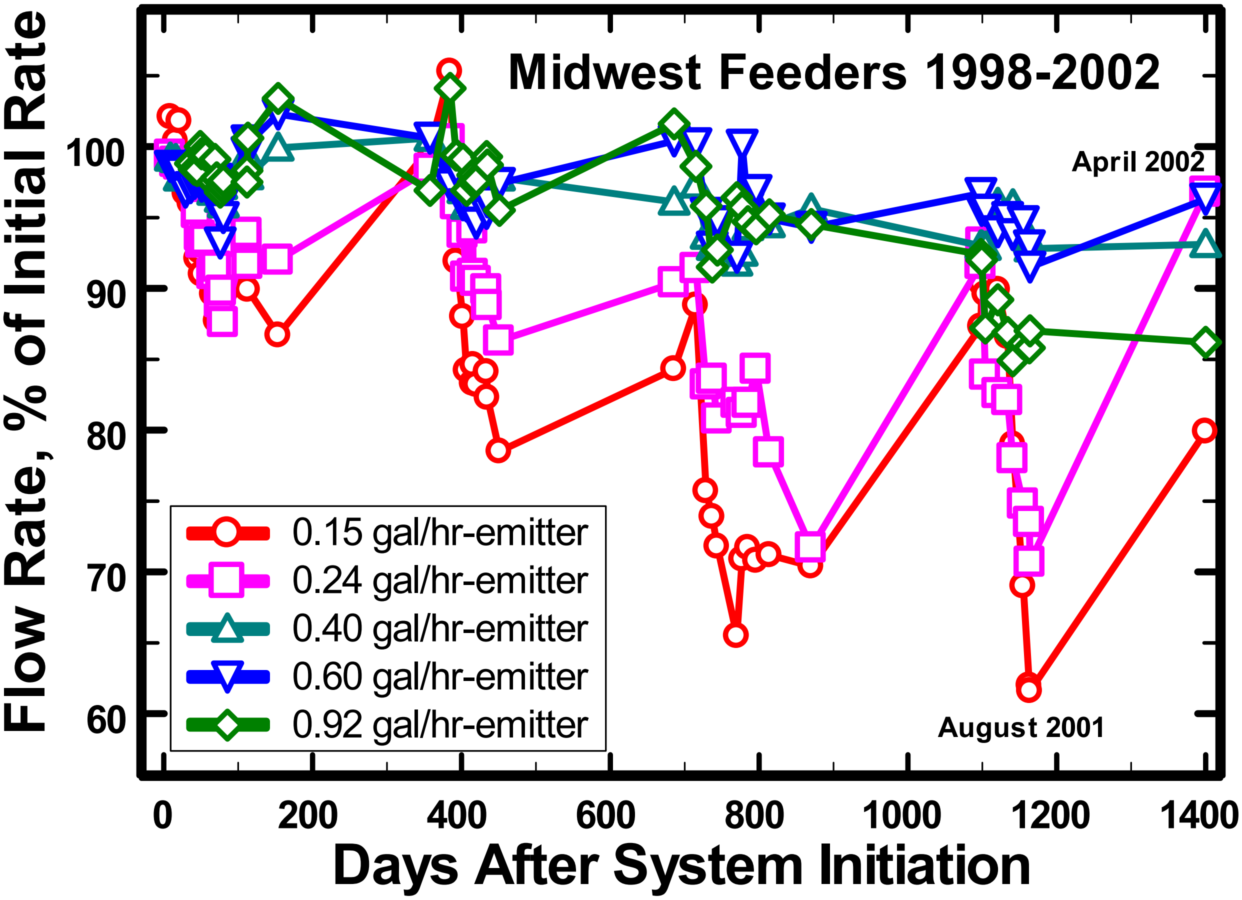

Figure 13. Decrease in emitter discharge during four seasons of operation of an SDI system with biological effluent at Midwest Feeders, Ingalls, Kansas, 1998 to 2002.

A second livestock effluent study using SDI was conducted in 2000 through 2001 at the KSU Northwest Research-Extension Center, Colby, Kansas (Lamm et al.,2006; Lamm et al., 2007). The overall objective of this project was to compare the environmental, cropping, and irrigation system impacts of swine effluent applied with SDI or simulated LEPA sprinkler irrigation. SDI tended to have greater corn yields (Table 4) and better nutrient utilization (Data not shown) than low-energy precision application (LEPA) center pivot sprinklers.

Table 4. Yield component and water use data for corn in a swine effluent study, KSU Northwest Research-Extension Center, Colby Kansas, 2000 to 2001.

Irrigation System & Effluent Amount	Irrigation inches	Applied N[1] lb/a	Grain yield bu/a	Water use[2] inches	WP[3] lb/acre-in
Year 2000					
SDI, Control	19.5	245	253	30.1	472
SDI, 1.0 inch effluent	19.5	229	252	30.4	464
SDI, 2.0 inches effluent	19.5	388	260	29.5	492
LEPA, 0.6 inches effluent	20.0	155	237	33.2	399
LEPA, 1.0 inches effluent	20.0	229	250	32.8	427
LEPA, 2.0 inches effluent	20.0	388	246	33.2	415
LSD P=0.05			NS	1.5	51
Year 2001					
SDI, Control	18.0	244	262	28.5	517
SDI, 1.0 inch effluent	18.0	209	270	27.4	553
SDI, 2.0 inches effluent	18.0	356	267	28.1	531
LEPA, 0.6 inches effluent	18.0	143	214	28.2	427
LEPA, 1.0 inches effluent	18.0	209	251	28.7	493
LEPA, 2.0 inches effluent	18.0	356	237	30.3	439
LSD P=0.05			22	NS	53
Mean of both years 2000 - 2001					
SDI, Control			258	29.3	495
SDI, 1.0 inch effluent			261	28.9	509
SDI, 2.0 inches effluent			263	28.8	512
LEPA, 0.6 inches effluent			225	30.7	413
LEPA, 1.0 inches effluent			251	30.8	460
LEPA, 2.0 inches effluent			241	31.7	427
LSD P=0.05			20	1.0	35

[1] Total applied N-P-K from the 3 sources: starter treatment at planting (30 lb/acre N + 45 lb/ac P_20_5), wastewater application, and the naturally occurring amount in the irrigation water (0.75 lbs/acre-in).

[2] Total of seasonal change of soil water storage in the 8-ft profile plus irrigation and precipitation.

[3] Water productivity (WP) is defined as grain yield in lbs/acre divided by total water use in inches.

Economics of SDI

SDI has not been typically used for row crop production in the Central Great Plains. Typically, SDI has much higher investment costs as compared to other pressurized irrigation systems such as full size center pivot sprinklers. However, there are realistic scenarios where SDI can directly compete with center pivot sprinklers for corn production in the Central Great Plains. As field size decreases, SDI can more directly compete with center pivot sprinklers because of increasing higher ratio of center pivot sprinkler (CP) costs to irrigated area (Figure 14). Small and irregular shape fields may be ideal candidates for SDI.

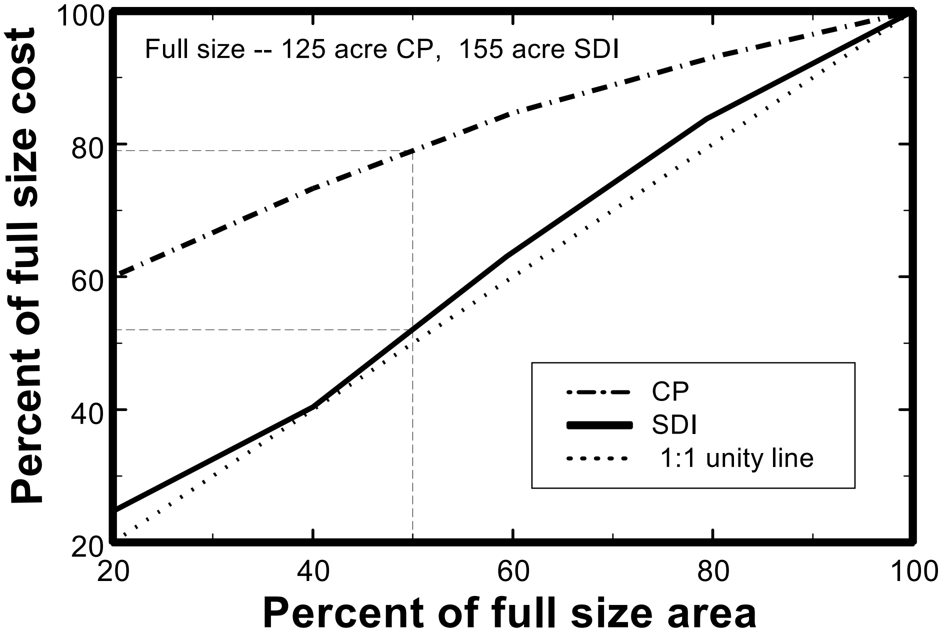

Figure 14. Center pivot sprinkler (CP) and SDI system costs as related to field size. (after O'Brien et al., 1997)

Economic comparisons of CP and SDI systems are sensitive to the underlying assumptions used in the analysis (Lamm et. al., 2003). The results show that these comparisons are very sensitive to size of CP irrigation system, shape of field (full vs. partial circle CP system), life of SDI system, SDI system cost with advantages favoring larger CP systems and cheaper, longer life SDI systems. The results are moderately sensitive to corn yield, corn harvest price, yield/price combinations and very sensitive to higher potential yields with SDI with advantages favoring SDI as corn yields and price increase. A Microsoft Excel spreadsheet template has been developed for comparing CP and SDI economics and is available for free downloading from the internet at http://www.ksre.ksu.edu/sdi/Software/SDISoftware.htm

System life of SDI

SDI system life must be at least 10-15 years to reasonably approach economic competitiveness with full sized center pivot sprinkler systems that typically last 20-25 years. Using careful and consistent maintenance, a 20 year or longer SDI system life appears obtainable when high quality water from the Ogallala aquifer is used. The system performance of the K-State SDI research plots has been monitored annually since 1989 with few signs of significant degradation (Figure 15). The benchmark study area has received shock chlorination approximately 2-3 times each season, but has not received any other chemical amendments, such as acid. The water source at this site has a TDS of 279, hardness of 189.1, and pH of 7.8. This water source would be considered a moderate chemical clogging hazard according to traditional classifications (Nakayama and Bucks, 1986). It is possible that the depth of the SDI system (16 to 18 inches) has reduced the chemical clogging hazards due to less temperature fluctuations and negligible evaporation directly from the dripline.

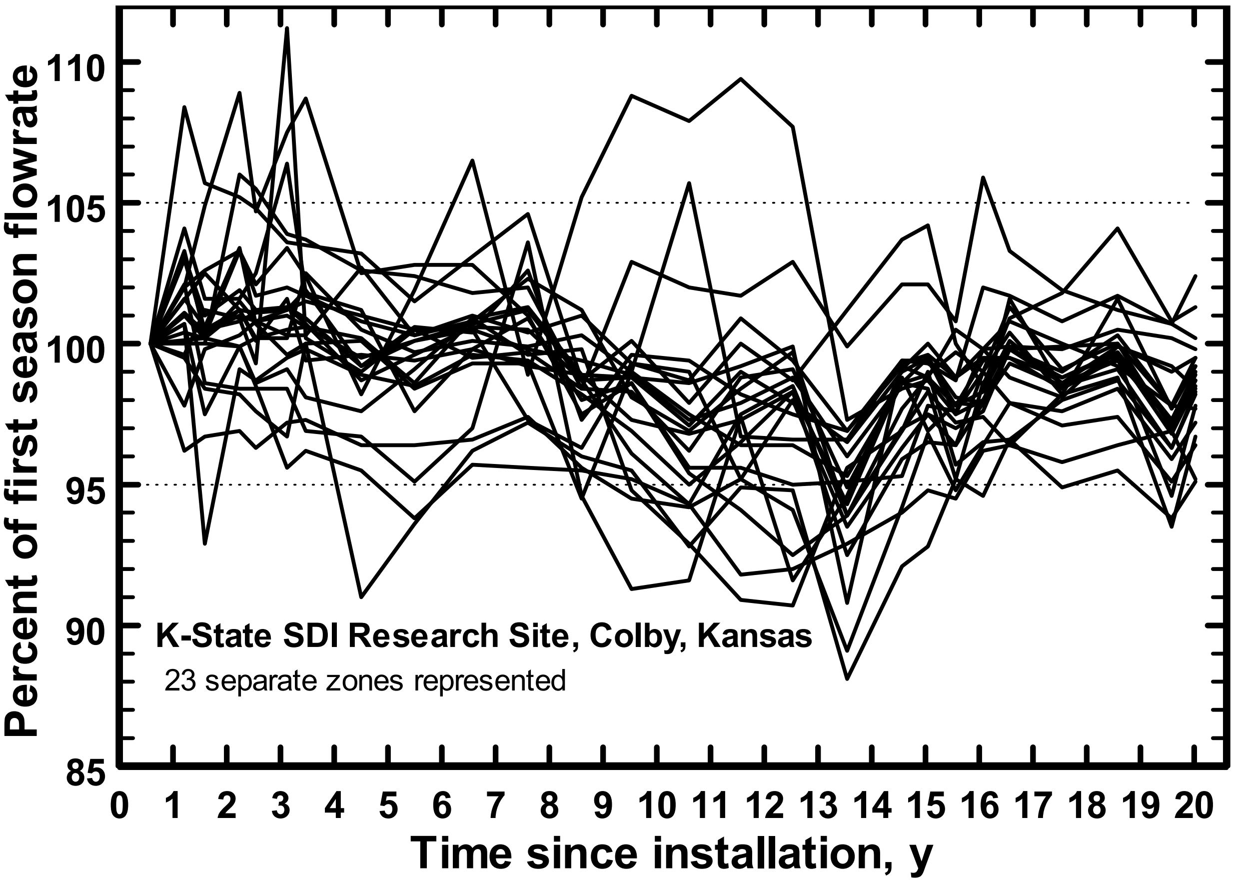

Figure 15. Stability in zone flowrates from the initial first season as related to time for an SDI system installed at Kansas State University, Colby, Kansas, 1989-2009.

Concluding Statements

Research progress has been steady since 1989. Much of K-State's SDI research is summarized at K-State's SDI Website, SDI in the Great Plains at http://www.ksre.ksu.edu/sdi/. Irrigators are watching the results of K-State closely. Some irrigators have begun to experiment with the technology and most appear happy with the results they are obtaining. It is K-State's hope that by developing a knowledge base in advance of the irrigator adoption phase that the misapplication of SDI technology and overall system failures can be minimized. Economics of the typical Great Plains row crops will not allow frequent system replacement or major renovations. Irrigators must carefully monitor and maintain the SDI system to assure a long system life. Continued or new areas of research are concentrating on optimizing allocations of water, seed, and nutrients, utilizing livestock wastewater, developing information about SDI use with other crops besides corn, soil water redistribution, water and chemical application uniformity, and finally system design characteristics and economics with a view towards system longevity.

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Several K-State faculty members have conducted and contributed to the progress of KSU SDI corn research over the years since 1989. These include, Freddie Lamm, Bill Spurgeon, Todd Trooien, Harry Manges, Danny Rogers, Mahbub Alam, Loyd Stone, Alan Schlegel, Gary Clark, Rob Aiken, Dan O'Brien, Troy Dumler, Kevin Dhuyvetter, Mark Nelson, Norm Klocke, Keith Harmoney, and Sandy Johnson.

[1] Mention of tradenames is for informational purposes only and does not constitute endorsement by the authors or by the institutions they serve.

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This paper is also part of a year-long SDI technology transfer effort in 2009 involving Kansas State University, Texas A&M University and the USDA-ARS and is funded by the Ogallala Aquifer Project. To follow other activities of this educational effort, point your web browser to http://www.ksre.ksu.edu/sdi/. Watch for this logo.

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Treatment of SDI Emitters Clogged with Manganese Compounds

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Abstract. *Dissolved manganese in irrigation water has contributed to emitter clogging of subsurface drip irrigation (SDI) systems in the Texas High Plains. During the 2002 growing season, areas of clogged emitters occurred in a 16-acre research field at the Texas AgriLife Research and Extension Center at Halfway, Texas. Water samples from the irrigation source were analyzed and SDI emitters in the affected areas were uncovered and examined in a laboratory setting. Evaluations indicated clogging was caused primarily by manganese oxides deposited inside SDI laterals and emitters. Observations of reactions of manganese compounds with combinations of acids and hydrogen peroxide (H_2O_2) resulted in a protocol that dissolved these oxides in open laboratory containers. Further tests examined pressurized sections of excavated, clogged SDI laterals with H_2O_2 / acid solutions for periods of up to 96 hours. This exercise led to the successful field treatment that cleared clogged emitters at the research site. Continued maintenance of the research system involved the injection of 2.5 ppm H_2O_2 in slightly acidic irrigation water during normal irrigation. Issues with the use of these procedures include human safety, due to the caustic nature of the required materials, and high chemical cost.*

Keywords. Subsurface drip irrigation, emitter clogging, manganese, Mn, hydrogen peroxide.

Introduction

Subsurface drip irrigation (SDI) can be the most efficient in-season irrigation application method in the Southern High Plains of Texas (Bordovsky and Porter, 2003, Colaizzi, et al., 2004) and its use is expected to increase as water supplies in the Ogallala aquifer decrease. However, associated with reduced pumping levels is the problem of decreased water quality.

More for SDI than any other delivery system, irrigation water quality is critical for long term performance due to the potential for emitter clogging. Drip emitter clogging results from physical, biological, and/or chemical factors. The physical threats to emitter clogging include suspended solids such as sand or plastic particles; biological threats from microbial slimes, algae, or root intrusion; and chemical threats associated with pH, iron, manganese, hydrogen sulfide, or dissolved solids. Critical levels of these constituents are reported in several publications (Rogers, et al., 2003, Burt and Styles, 2007, and Nakayama and Bucks, 1986).

In the summer of 2002, SDI emitter clogging caused severe drought stress to cotton plants in areas within a 16-acre research field at the Texas AgriLife Research Center, Helms Research Farm at Halfway, Texas. Irrigation zone flow rates were near the design rates in September 2001 and during initial pre-plant irrigation in 2002, however they soon declined. Further investigation and analysis of residue and water samples by the Soil, Water, and Forage Testing Laboratory (Texas A&M University, College Station, TX) led to the conclusion that the primary constituents causing emitter clogging were manganese oxides. Figure 1 shows drip laterals and clogged emitters removed from the problem SDI field.

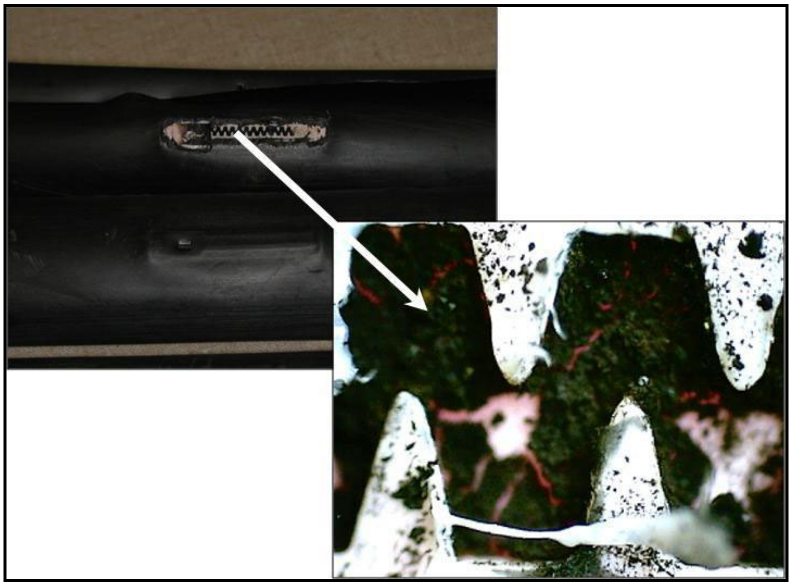

Figure 1. Clogged SDI emitters removed from research test plots at the Texas AgriLife Research Center, Halfway, 2002.

The critical dissolved manganese (Mn) levels in irrigation water that result in “minor”, “moderate”, and “severe” emitter clogging concerns are <0.1 ppm, 0.1-1.5 ppm, and > 1.5 ppm, respectively (Nakayama and Bucks, 1986). A 2002 water sample taken from the well supplying the emitter-clogged drip field had Mn levels of 0.15 ppm, which was just within the moderate level of risk for Mn clogging.

This water well had been treated for algae by chlorination in 2001 (Cotey Chemical Corp., Lubbock, Texas). The assumption was made that the algae problem was aggravated by the use of drip oil required to lubricate the line shaft of the turbine pump. Due to the history of algae growth and the presence of carbonates in the irrigation water supply, the SDI system was flushed every 2-3 weeks during the growing season, and acidized and chlorinated prior to and following pre-plant irrigation and at the end of each growing season. Chlorinated water was left in the SDI system from the fall of 2001 to spring of 2002 as has been done with several drip systems at the research center since

1996. It is hypothesized that over time, and particularly over this winter, the chlorine used to treat biological residues also oxidized the available Mn in the water resulting in beginning of significant emitter clogging problems.

Information is available on methods to prevent Mn precipitation in water. These include the use of phosphate compounds (sequestering agents), ion exchange water softeners, oxidizing filters, aeration followed by filtration, and chemical oxidation followed by filtration. There were, however, few known sources of information on methods to recover a SDI system clogged with Mn and Mn compounds. The objective of this paper is to describe the laboratory and field process used to remove Mn compounds from a SDI system at the Helms Research Farm.

Laboratory Evaluations

Field installation of the SDI system was in 2000 with 2001 being the first full year of crop irrigation. Drip laterals had emitter spacings of 20 inches and emitter flow rates of 0.16 gh^{-1} at 10 psi (Typhoon emitter, Netafim Irrigation, Inc, Fresno, CA). Lateral wall thickness was 13 mil. Seven zones were individually metered with flow rates and pressures recorded on a daily basis during the 2001 growing season. No variation from the design pressures and flows were noticed until June 2002. At that time drip laterals were uncovered and flow measurements from individual emitters were obtained with flows ranging from zero up to the design rate. By July, areas of cotton plants were visibly water stressed. The principle location of clogged emitters was at lower elevations within the 16-acre site. Sections of drip laterals were uncovered and removed from the field for laboratory evaluation.

Dissolving manganese oxides

A black powdery material was obtained from drip lateral walls, flush water (following water evaporation), and emitters of the affected zones. The material was a combination of manganese oxides and very fine mineral or sand particles. In an attempt to dissolve the Mn compound, it was mixed in open containers with various levels of different acids and then different concentrations of hydrogen peroxide (H_2O_2). With the exception of prohibitively high acid concentrations the Mn was not dissolved.

Based on a method to extract manganese oxides from soil nodules using H_2O_2 in a 3 pH solution (Taylor, et al.,1964), combinations of H_2O_2 and acid solutions were mixed with the Mn material. Hydrogen peroxide rates ranged from 3%, as used by Taylor, et al. (1964), down to 0.0312%. These H_2O_2 quantities were mixed with acid solutions ranging from 0 to 8 pH. A qualitative evaluation of the %Mn dissolved was periodically recorded for up to 48 hours.

The results were promising. Figure 2 shows two jars containing 0.02 g of the Mn compound in 16 oz. of irrigation water with H_2O_2 at 0.125%. The pH of the container on the left was 7.6 while that of the container on the right was 6.5. Only residual sand particles were visible in the right container as the Mn had been dissolved. The time required to dissolve the material at room temperature was within seconds.

Figure 2. Jars containing Mn at 0.15 g material/gal of irrigation water, both at 0.125% H_2O_2 concentration. The pH of the container on the left was 7.6; the pH of the container on the right was 6.5.

The quantity of Mn material dissolved in different solutions having H_2O_2 concentrations ranging from 0 to 3% using muriatic acid or N-pHuric™ to lower pH is shown in Figure 3. At pH 3, 90% of the Mn compound was dissolved at 0.0312% H_2O_2 in six hours. The acid source did not change the outcome. Due to its relative safety, N-pHuric™ (Agrium, Calgary, Canada) which contains 49% equivalent sulfuric acid and 15% of water soluble organic nitrogen was used for the remaining evaluations.

Figure 4 displays the relative quantity of Mn material dissolved in solutions having acidity ranging from 0 to 7 pH, with and without H_2O_2. This, as well as previous figures, show relatively small levels of H_2O_2 dissolved the troublesome compound, but only if the pH of the solution was below 7. Acid alone was not a reasonable means for opening clogged emitters with this type Mn material.

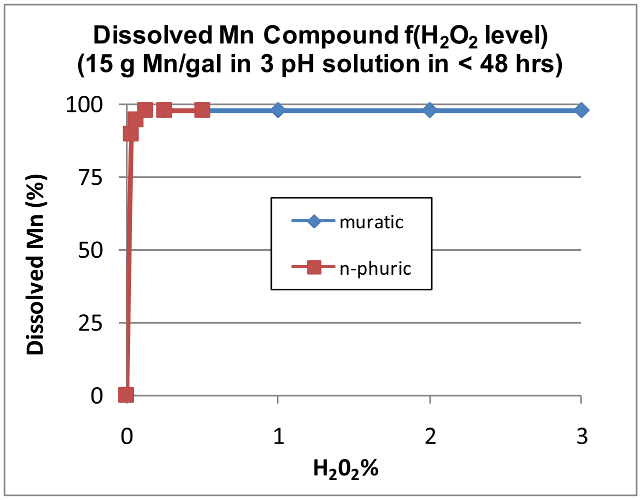

Figure 3. Percent of Mn material dissolved in solutions having H_2O_2 concentrations of 0 to 3% using muriatic acid or N-pHuric to lower solution pH.

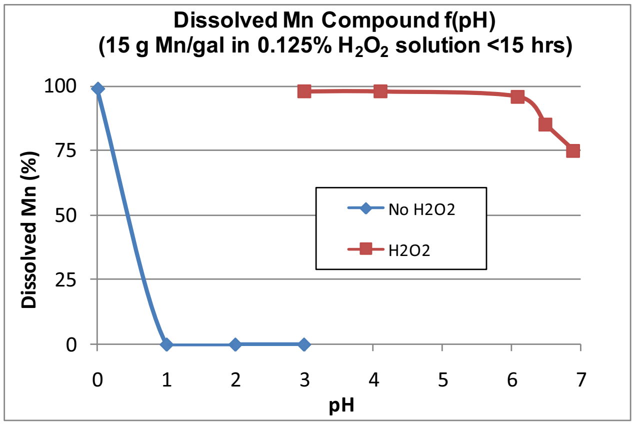

Figure 4. Percent of Mn material dissolved in solutions having pH ranging from 0 to 7, both with and without H_2O_2 in the solution.

Opening clogged emitters

After successfully dissolving Mn with H_2O_2 / acid solutions in open containers, these solutions were used in attempts to open sections of SDI drip laterals with clogged emitters in the lab. Drip laterals having at least one clogged emitter were placed in pressure controlled test stands to determine the effect that combinations of H_2O_2 concentrations, pH levels, and operating pressures had on opening emitters. All emitters were from the problem field, completely clogged (zero flow), and had undergone all field treatments (discussed below) through mid August. The tests involved closing one end of the lateral, filling the lateral with a solution, attaching a constant pressure source to the other lateral end, and visually monitoring pressure and emitter flow over time.

Under identical but separate treatments, two of three emitters returned to 100% design flow after 3.5 and 6 hours, respectively, when treated with 3% H_2O_2 solution at pH 3 and pressured to 30 psi (Figure 5). Sand particles as well as additional Mn compounds were found in the third emitter after dissection following the test. Pressure effect on unclogging emitters is shown in Figure 6. Clogged emitters were treated with a 0.5% H_2O_2 solution at pH 3 and pressurized to 12 then 30 psi versus continuous 30 psi. Immediately elevating the lateral pressure to 30 psi (emitter P3) versus starting with 12 psi then changing to 30 psi (emitters P1 and P2) resulted in full emitter flow in 4.75 hours instead of 23.5 and 33 hours, respectively. Although SDI installations are typically designed for 20 psi or less, pressure greater than standard operating pressures had major impact on the time required to open clogged emitters. The time required to open emitters was also affected by the pH and H_2O_2 level of water forced through the emitters (Figure 7). Relative time for emitters to clear were 3.5, 20, and 78 hours from solution treatments with 0.25% H_2O_2 at pH 3, 0.25% H_2O_2 at pH 4.7, and 0.5% H_2O_2 at pH 4.7, respectively with pressure at 30 psi. For these three emitters, elevated pH and reduced H_2O_2 levels increased time for full flow. In all evaluations, once initial flow started, emitters typically cleared within a few hours.

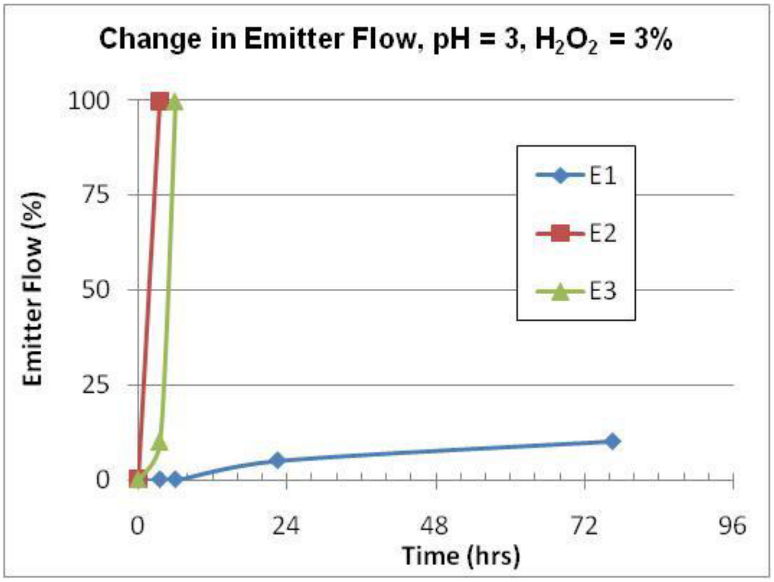

Figure 5. Relative emitter flow over time of three random clogged emitters treated with 3% H_2O_2 solution at pH 3 and pressurized at 30 psi.

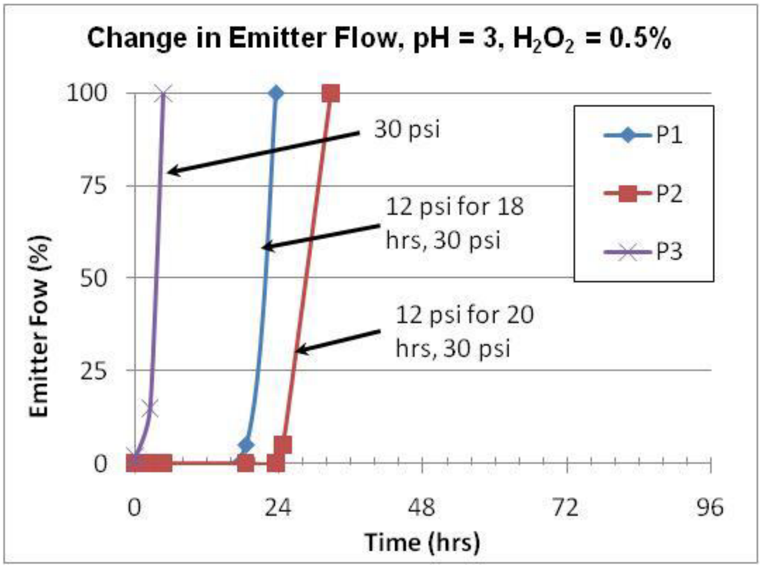

Figure 6. Relative emitter flow over time of three clogged emitters treated with a 0.5% H_2O_2 solution at pH 3 and pressurized to 12 then 30 psi versus continuous 30 psi.

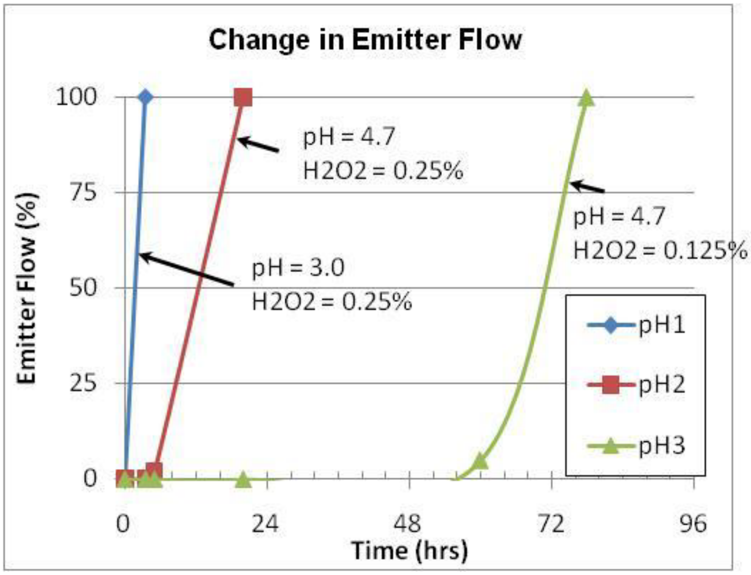

Figure 7. Relative emitter flow over time of clogged emitters treated with 0.25% H_2O_2 at pH 3, 0.25% H_2O_2 at pH 4.7, and 0.5% H_2O_2 at pH 4.7 solutions with pressure at 30 psi.

Field Treatments

As noted earlier, flow rates of certain SDI zones in the 16-acre research field had begun to decrease by June 2002. Several field treatments were conducted in an attempt to restore zone flow rates and pressures prior to the laboratory tests. These procedures included chlorinating the water supply well (3 times), flushing SDI laterals (5 times), treating clogged zones with 3% H_2O_2 (1 time), and continuously chlorinating water as seasonal irrigations progressed. A list of significant treatment events and the resulting zone flow of one severely clogged zone (Zone 3) and a less severely clogged zone (Zone 6) from May until flow was re-established in September, 2002 is given in Table 1 and Figure 8, respectively. Attempts to alleviate the problem by initial field treatments with H_2O_2 and chlorination may have further increased emitter clogging.

Initial hydrogen peroxide and continuous chlorination treatments

One procedure recommended by a local SDI service provider for treating Mn in SDI systems was to backfill a 3% H_2O_2 solution into the flush valves of the drip system using sufficient volume to fill all drip tapes that might have clogged emitters. This procedure was completed in early July. The volume of the SDI drip laterals and manifold system were determined to be slightly less than 500 gal per zone. A solution of 950 gal of well water and 50 gal of 50% H_2O_2 were mixed in a 1000 gal tank trailer and two zones were

Table 1. Chronology of events leading to the opening of SDI emitters clogged with manganese compounds at the Texas AgriLife Research Center, Halfway, TX, 2002.

Date	Chlorinate Well	Start Seasonal Irrigation	Obtain Water Sample From Well	Acid & Chlorine Treatment of SDI Lines	Flush SDI Lines	Continuous Chlorine Injection @ Well	H_2O_2 Treatment	Filter Mesh Size	Continuous H_2O_2 @ 6.8 pH @ Well	Start Emitter Cleaning Process	Lab Evaluation of H_2O_2 at low pH
28-May	x							120			
10-Jun		x						120			
12-Jun			x	x				120			
8-Jul	x				x			120			
10-Jul							Zone 2 & 3	120			
12-Jul						x		120			
15-Jul					x	x		120			
25-Jul					x	x		120			
31-Jul	x					x		120			
2-Aug					x	x		120			
7-Aug						x	Zone 1,4, & 7	120			
8-Aug					x	x		120			
14-Aug						x		120			x
15-Aug						x		200			x
16-Aug					x	stop chlorine		200			x
23-Aug					x			200			x
23-Aug								200	x		x
27-Aug					x			200	x		
30-Aug			x					200	x		
2-Sep					x			120	x	Zone 1,4,5,6	
4-Sep					x			120	x	Zone 2, 3, 7	

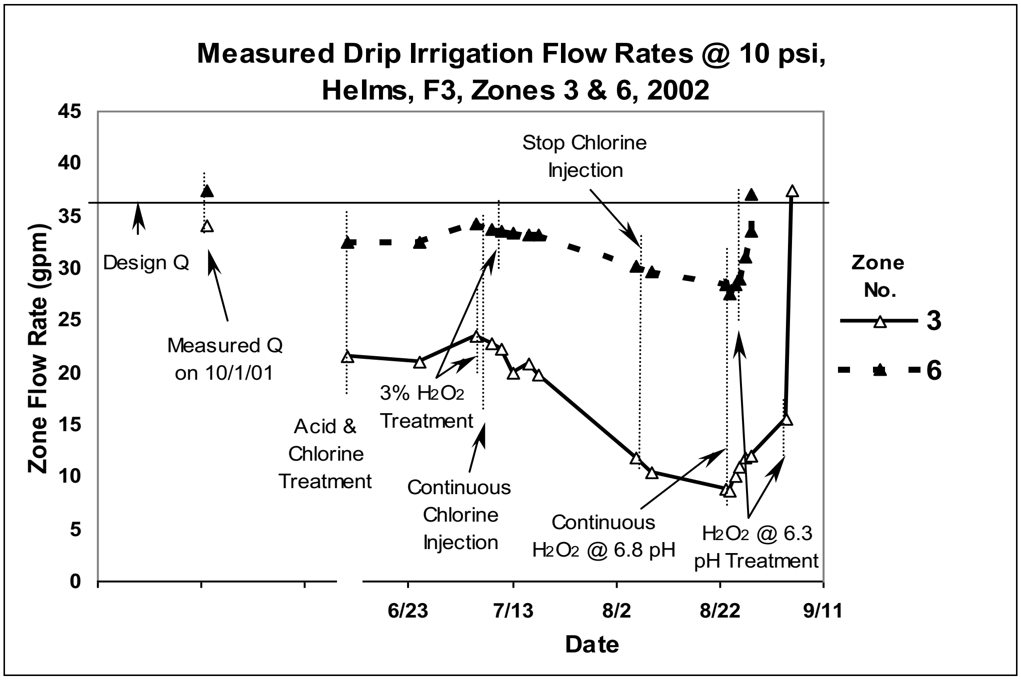

Figure 8. Flow rates and treatment events of a severely clogged zone (Zone 3) and a less severely clogged zone (Zone 6) from May until full emitter flow was reestablished in September, 2002.

treated. This solution was pumped into flush valves at a rate of 30 gpm until reaching the filter station. The solution was left in the drip lines and flush and header lines for 18 hours with the header line open to the atmosphere.

The 3% H_2O_2 solution reacted with the Mn compound on the inside walls of the drip tubing and drip emitters. Violent bubbling appeared to suspend the black Mn particles, however the solution did not dissolve them.

Both zones were then flushed with filtered well water as pressure at the zone inlet was restricted to 1 psi or less. The initial flush water was black from the Mn compounds released from the walls of the drip laterals. Flush water began clearing after 45 min, or after 3 to 4 exchanges in plumbing volume. The low pressure flushing continued for an additional 2 hours until the water cleared. The flush valves were closed and the zones were pressured to 3 psi for 16 hours. The zones were again flushed with the flush water clearing after several minutes. The zones were then placed back into a regular irrigation cycle.

Several emitters from the affected area were uncovered and observed during and for several days following the treatment. Based on these observations as well as zone flow rates and pressures, the H_2O_2 treatment had no immediate beneficial effect on the clogged emitters. The treatment, however, removed significant amounts of the Mn compound that would have continued to cause emitter clogging.

Chlorination (oxidation) and filtration is one method of removing manganese from water. Following the initial H_2O_2 treatment (early July) until August 10, chlorine in the form of 12% sodium hypochlorite was continually injected during irrigations at the irrigation well. The well was 1600 ft from the filter station and was thought to provide sufficient time for chemical mixing and Mn precipitation prior to filtration. The filter was a Netafim USA, Disc Kleen Filter (PN 26ASK2A3-120, Fresno, CA) with 130 micron discs and then later, 200 micron discs. This procedure failed to improve the situation as zone flows continued to decline as more emitters were clogged (Figure 8). The apparent problem with this procedure was insufficient time for Mn precipitation and / or the inability to filter the fine Mn particles.

Unclogging emitters with hydrogen peroxide and acid

Cost of materials to clean emitters on a field scale was a major concern, therefore the initial H_2O_2 / acid field treatment used very low levels of H_2O_2 in 6.8 pH irrigation water. Hydrogen peroxide was injected at the well at 2.5 ppm downstream from acid introduction. This process continued for 7 days in the normal irrigation cycle with notable increases in flow of all zones. However numerous emitters in the highly clogged zones did not recover. Based on the lab experiments, a field emitter reclamation process was outlined and executed.

The general procedure used at the Texas AgriLife Research and Extension Center, Helms Research Site, Halfway, Texas to open SDI emitters clogged with manganese oxide compounds was:

1) Several drip lateral sections with adjacent clogged emitters were uncovered in the zone to be treated. Water from the zone was drained and sections of drip lateral containing clogged emitters were replaced with lateral sections having new emitters

with the design flow rate. During the cleaning process, differences in flow rates of the adjacent new and clogged emitters were monitored to determine the effect of the process.

2) The pH of irrigation water was lowered at the well to 6.3 using N-pHuric™.
3) Drip laterals in the target zone were flushed with filtered water until clear.
4) With the flush valve open, H_2O_2 was injected prior to filters at a rate resulting in a 0.1% H_2O_2 solution with this rate maintained until it reached the flush valve. The flush valve was closed; the water flow and H_2O_2 injection stopped; and the solution left in the drip laterals overnight (16 hours).
5) Simultaneously zone and flush valves were opened and chemical injection restarted thereby resuming the flow of 0.1% H_2O_2 in 6.5 pH irrigation water into each zone.
6) Flush water was allowed to clear before closing the flush valve and pressurizing the target zone to normal operating pressure (10 psi). The zone flow rate was recorded.
7) Injection rates were readjusted to maintain pH and H_2O_2 concentrations as zone pressures were increased to 20 psi. As emitters began to open, zone flow increased and chemical concentrations adjusted to maintain desired levels. This process continued for 6 hours in Zone 3, the zone most severely clogged. Terminating this part of the process was based on evidence of emitter flow from previously clogged emitters. Hydrogen peroxide bubbles "erupted" on the soil surface above covered emitters that were not fully clogged.
8) After this injection period, the H_2O_2 concentration was reduced to 2.5 ppm at 6.8 pH and 20 psi pressure for an additional 6 hours. Pressure was then readjusted to normal levels and zone flow rates recorded. Throughout this process, uncovered emitters, zone flow rates and pressures were monitored to determine the effectiveness of the cleaning procedure.
9) After all zones were treated, the normal operation cycle for irrigation was resumed. In all zones, flow rates recovered to the original design level.

Figure 9 shows the effects of emitter clogging on cotton growth in 2002 and the result of the reclamation process at the same locations in 2003.

Figure 9. Effects of SDI emitter clogging on cotton production in 2002 (left) and cotton in 2003 at the same location following SDI system reclamation (right).

Long Term Considerations

System maintenance and costs

Over 100 acres are currently irrigated with subsurface drip at the Texas AgriLife, Helms Research Farm from two wells each having Mn levels greater than 0.1 ppm. To prevent emitter clogging, maintenance treatments have been used during irrigation from 2003 to 2009. The treatments consisted of the continuous injection of N-pHuric™ using a pH controlled injection pump to achieve 6.8 pH irrigation water, then adding dilute H_2O_2 (4.54 % solution) to reach a final concentration of 2.5 ppm. Manganese oxide buildup on system components was monitored by observing water supply lines through site glasses at the filter stations, by recording zone flow rates, and by noting color variations in flush water.

The maintenance procedure was changed in 2005 in an attempt to reduce the cost of materials. Injections of chemical were modified from continuous injection to injection every other 2-week period. At the end of periods without injection, brown and black deposits were seen on the site glasses at filter stations. At this point, zone flows were not yet affected. Re-establishing H_2O_2 / acid injections at the maintenance rates reduced these deposits within 2 weeks. There has been no evidence of emitter clogging since 2002.

The cost of maintenance treatments from 2003 to 2006 is given in Figure 10.

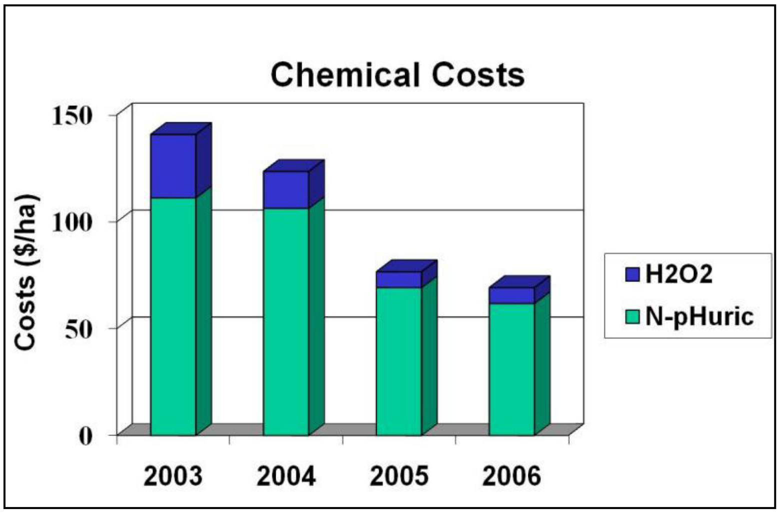

Figure 10. Hydrogen peroxide and acid costs for maintenance of SDI systems at the Texas AgriLife Research Center, Helms Research Farm, 2003-2006.

Mn build up in the soil

Dissolved Mn was kept in solution using H_2O_2 in 6.8 pH irrigation water. In September of 2003, an array of soil samples were taken around drip laterals at four locations within the problem research field to quantify any increase of Mn in the soil. High Mn concentrations can be toxic to cotton plants.

Manganese found in these soil samples ranged from <1 ppm to slightly greater than 5 ppm. Figure 11 shows soil sample locations and average residual Mn concentrations around drip laterals in treatments irrigated at approximately 80% crop evapotranspiration. Although Mn concentrations have appeared to follow SDI wetting patterns, the quantities of this element are well below toxic levels for cotton plants. Mn concentrations in the root zone have continued to be monitored with no significant increases since 2003.

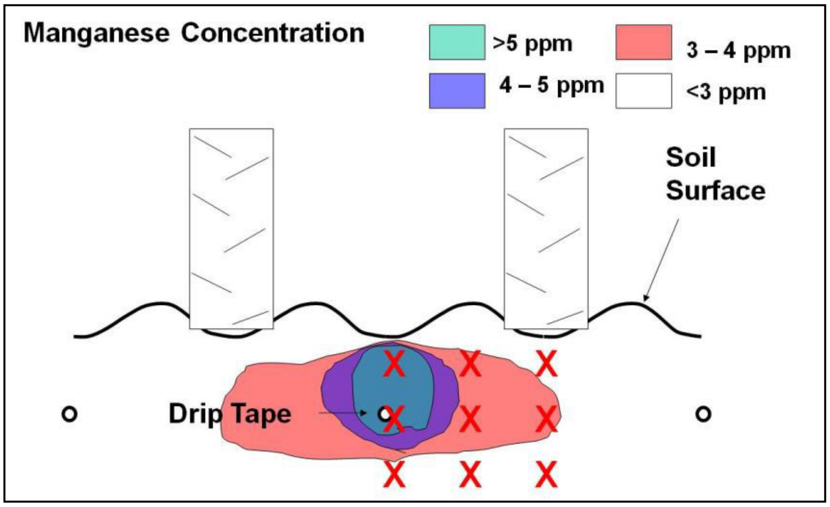

Figure 11. Soil sample locations and average residual manganese concentrations around SDI laterals, Helms Farm, Halfway, TX, 2003.

Summary and Conclusions

Dissolved manganese in irrigation water has contributed to emitter clogging of subsurface drip irrigation (SDI) systems in the Texas High Plains. Laboratory observations of reactions of manganese compounds from clogged SDI zones with acids and H_2O_2 resulted in a protocol that dissolved these oxides in open containers. Further tests involved pressurizing sections of clogged SDI laterals with H_2O_2 / acid solutions for periods of up to 96 hours. This led to successful field treatments that cleared clogged emitters at the research site. Maintenance of the SDI system included the continuous injection of 2.5 ppm H_2O_2 in slightly acidic irrigation water during normal irrigations.

Issues with the use of these procedures include human safety, due to the caustic nature of the chemicals, and high chemical cost. Also elevating drip lateral pressures above manufacturer's recommendations can void warranties and possibly damage the drip system.

Alternative maintenance methods are being considered due to safety and cost issues.

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Impact of Management on the Life Expectancy of Drip Systems

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Abstract: A successful maintenance program may increase the longevity of subsurface drip irrigation (SDI) systems. This study evaluated ten subsurface drip irrigation systems in 2008 and eight systems in 2009 that have longevities between six and twenty years. The system performance parameters: Christiansen's Uniformity Coefficient (CUC) and Low Quartile Distribution Uniformity (DUlq) was assessed for eighteen SDI systems and their maintenance practices were documented. The longevity of the system may be related to the water quality of the aquifer. The aquifer does not present any major problem related to chemical compounds that can enhance clogging problems. The uniformity of the ten systems evaluated in 2008 was greater than 79.3%. In 2009, two evaluated systems had low irrigation uniformities (CUC of 57.2 and 61.8%) Maintenance practices among farmers were very similar. Most of the farmers flush their filters daily for at least 1.33 minutes and flush the manifolds once a year. Farmers inject sulfuric acid once a year lowering the pH to less than 3.5. Others use N-pHuric instead of the sulfuric acid. One of the farmers with low CUC has not yet injected sulfuric acid into his system. The sulfuric acid that most farmers use is 95% and they apply it at approximately 0.94 L/ha (1 gal/10 acres). Some farmers inject chlorine every year, but others just every 7 years. The farmer that had the most clogging problems did not use chlorine. The chlorine is Univar's sodium hypochlorite, which is 12% and they apply it at approximately 0.47 L/ha (1 gal/20 acres). One of the systems evaluated in 2009 had very low uniformity which was probably due to the very low operating pressure. A good maintenance program and the use of good quality water should increase the longevity of the SDI system.

Keywords: performance evaluation, microirrigation, chlorination, acidification, chemigation, subsurface drip irrigation.

Introduction

Subsurface drip irrigation (SDI) systems are very uniform when properly designed and installed and distribution uniformities greater than 90% can be obtained with these systems (Enciso et al., 2002 and 2003). Considering the high uniformity of these systems, fertilizers and chemicals can be applied through the water in small and frequent quantities, increasing water application and nutrient utilization efficiencies (Lamm and Camp, 2007). Chemical losses through deep percolation or drifting from sprinklers can be minimized (Bordovsky, 2003). Beginning in the early 1980s, cotton producers in West Texas began to install subsurface drip irrigation (SDI) systems to stretch declining groundwater resources. Henggeler (1995) reported that adoption of SDI greatly improved lint yield and water use efficiency. Several commercial producers noted an average 27% increase in yield over surface (furrow) irrigation, with yield increases 2.5 times greater than dryland. Regular maintenance has prevented clogging, even in systems that were installed more than 15 years ago. It is necessary to determine how these systems are operating after all this time and determine how maintenance has helped to prevent emitter clogging problems. The difficulty in evaluating the systems is that the dripline is typically buried at approximately 33 cm (13 inches) for SDI systems on continuous cotton in Texas. Methodology to assess the SDI system performance and how maintenance programs might affect longevity are needed to assure the sustainability of irrigated agriculture in the region. The main objective of this study was to evaluate the uniformity of ten SDI systems with a life greater than seven years. Another objective was to document maintenance practices that permit the long term sustainability of SDI systems which is the predominant irrigation system in several areas of West Texas. Considering the large investment needed for SDI, it is vital to extend their lifetime with proper maintenance. By assessing the performance of the systems, we can evaluate the effectiveness of the various maintenance programs.

Procedures

Ten farms were selected in 2008 and eight in 2009 to evaluate the SDI system performance and evaluate the maintenance program in the resultant system performance and longevity. The systems were selected according to system age and with the recommendations of collaborating farmers. Farmers suggested which specific systems they wanted evaluated considering the water quality of the aquifer and the producer's system operating and maintenance practices. The farmers were located either in the TransPecos or the St. Lawrence area of Texas. Hydraulic characteristics of the SDI systems, such as the emitter design pressure and flowrate, emitter spacing were obtained from the producer. Emitter flowrate and pressure at the lateral was recorded during the evaluation. Emitter flowrate data was collected from 18 points for each SDI system. The data was collected from 18 random locations within a single SDI zone. The data was used to determine the Christiansen's Uniformity Coefficient (CUC) and the Low Quartile Distribution Uniformity (DUlq).

The Low Quartile Distribution Uniformity is

$$\mathrm{DUlq} = \frac{avg.\ low - quarter\ depth}{avg.\ depth\ of\ water\ accumulated\ in\ all\ the\ containers}$$

Christiansen's uniformity coefficient is defined as

$$CU = \frac{100\ [1 - (\sum |\ (X - x)\ |)}{\sum X}$$

where X is the depth (or volume) of water in each of the equally-spaced catch containers and *x* is the mean depth (or volume) of water in all the catch cans.

Results

Water Analysis

The irrigation water was evaluated for 7 of the 10 sites in 2008 and in 8 sites in 2009. The irrigation water was generally good quality water pumped primarily from the Edwards Trinity Plateau and Ogallala aquifers (Table 1a for 2008 and 1b for 2009) with small amounts of sodium salinity. Site C had the greatest salinity from the 2008 samples with 2352 mg/L of total dissolved solids (TDS). Site K had the greatest salinity of the 2009 samples with 3541 mg/L of total dissolved solids (TDS). Cotton has a relatively high tolerance for salinity and since it is grown continuously in this region, the water has not been a problem. Water hardness is expressed as the combination of calcium and magnesium mg/L. Most values of the combined calcium and magnesium are over 100 mg/L and special precautions are necessary if phosphoric acid is to be injected into the system. The water should be acidified before phosphoric acid is injected to avoid the formation of phosphates that could precipitate in the dripline and clog its emitters. This is often done by mixing the phosphoric acid with N-pHuric[1] (Urea-Sulfuric- Acid). Alternatively, but a less preferable method of avoiding phosphate precipitation is to inject the phosphoric acid at a fast rate to quickly lower the pH below 4 before precipitates can form. The injection of fertilizers containing phosphorus will be a problem if proper precautions are not taken. Iron and Manganese can also represent a clogging potential when the iron concentrations of the water are greater than 0.6 mg/L and when sulfides greater than 2.0 mg/L are present. The water of the study sites had very low concentrations of iron and magnesium; therefore clogging problems caused by these elements did not represent a threat.

Table 1.a. 2008 water quality parameters for the seven of the ten older SDI systems that were evaluated in West Texas.

Parameter analyzed	Site							
	A	B	C	D	E	F	G	Units
Calcium (Ca)	104	129	235	151	101	112	96	mg/L
Magnesium (Mg)	36	41	119	61	39	23	32	mg/L
Sodium (Na)	131	151	334	202	119	79	128	mg/L
Potassium (K)	6	6	16	9	6	6	6	mg/L
Boron (B)	0.80	1.05	1.34	1.26	0.70	0.49	0.79	mg/L
Carbonate (CO_3)	0	0	0	0	0	0	0	mg/L
Bicarbonate (HCO_3)	269	260	238	245	262	279	269	mg/L
Sulfate (SO_4-)	293	350	1128	579	306	143	248	mg/L
Chloride (Cl^-)	95	133	274	190	90	105	102	mg/L
Nitrate-N (NO_3-N)	8.35	9.98	8.70	4.92	5.05	3.67	6.34	mg/L
Phosphorus (P)	0.04	0.04	0.05	0.04	0.03	0.05	0.04	mg/L
pH	7.30	7.30	7.20	7.30	7.40	7.30	7.30	-
Conductivity	1223	1423	2890	1807	1148	960	1146	µmhos/cm
Hardness	24	29	63	37	24	22	22	grains CaCO3/gallon
Hardness	410	491	1074	629	412	373	370	mg/L CaCO3
Alkalinity	221	213	195	201	215	229	221	mg/L CaCO3
Total Dissolved Salts (TDS)	944	1081	2352	1443	929	750	889	mg/L
SAR	2.8	3.0	4.4	3.5	2.5	1.8	2.9	-
Iron (Fe)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	mg/L
Zinc (Zn)	< 0.01	0.02	0.04	0.08	0.06	0.67	0.09	mg/L
Copper (Cu)	0.02	0.01	0.02	0.02	0.14	0.07	0.02	mg/L
Manganese (Mn)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	mg/L
Charge Balance (cation/anion*100)	101	103	102	98	100	102	101	-

Table 1.b. 2009 water quality parameters for eight older SDI systems that were evaluated in West Texas.

Parameter analyzed	Site								
	K	L	M	N	O	P	Q	R	Units
Calcium (Ca)	526	95	91	184	214	116	87	91	mg/L
Magnesium (Mg)	105	27	38	60	59	26	26	27	mg/L
Sodium (Na)	462	95	101	168	125	122	106	75	mg/L
Potassium (K)	11	7	6	10	11	9	8	6	mg/L
Boron (B)	1.39	0.51	0.63	1.01	0.84	0.57	0.49	0.53	mg/L
Carbonate (CO_3)	0	0	0	0	0	0	0	0	mg/L
Bicarbonate (HCO_3)	183	265	258	234	208	258	291	252	mg/L
Sulfate (SO_4-)	1,706	246	273	646	709	270	227	217	mg/L
Chloride (Cl^-)	517	81	96	174	119	99	94	70	mg/L
Nitrate-N (NO_3-N)	29.6	4.2	5.66	7.63	7.4	28.76	1.06	5.04	mg/L
Phosphorus (P)	0.17	0.06	0.04	0.06	0.09	0.39	0.03	0.03	mg/L
pH	7.10	7.51	7.48	7.28	7.32	7.35	7.62	7.5	-
Conductivity	4,100	990	1,077	1,775	1,674	2,120	1,130	890	µmhos/cm
Hardness	102	20	22	41	45	23	19	20	grains CaCO3/gallon
Hardness	1,747	347	384	709	777	395	325	337	mg/L CaCO3
Alkalinity	150	217	211	192	171	211	238	207	mg/L CaCO3
Total Dissolved Salts (TDS)	3,541	820	871	1,485	1,453	929	840	744	mg/L
SAR	4.8	2.2	2.3	2.7	2.0	2.7	2.6	1.8	-
Iron (Fe)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	mg/L
Zinc (Zn)	<0.01	<0.01	0.01	0.03	<0.01	0.06	<0.01	<0.01	mg/L
Copper (Cu)	0.03	0.01	0.04	0.02	0.02	0.02	0.01	0.01	mg/L
Manganese (Mn)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	mg/L
Charge Balance (cation/anion*100)	100	93	94	95	96	91	92	92	-

Evaluations of the SDI Systems

The ten SDI systems evaluated in 2008 had been in place between 8 and 20 years and the eight systems evaluated in 2009 had been in place between 6 and 12 years. Although there were older SDI systems that could have been selected, they were only being used occasionally to irrigate pecan trees. The original designs for none of the evaluated systems could not be located, but the emitter spacing and nominal emitter flow-rate was obtained (Table 2a for 2008 and Table 2b for 2009). The brand of the dripline, diameter of the dripline and fertilizers that were used by the farmers are shown in Table 3a and 3b. During 2008, System I had the least operating pressure [24 kPa (3.5 PSI)] and also had the least DU_{LQ} (79.2%) and least CUC (79.3%) which is probably indicating that this system was being operated below a minimum threshold operating pressure necessary for good performance. The Christiansen's uniformity coefficient and the DU_{LQ} was greater than 85% for 7 of the 10 systems which had a average lifespan to date of 11.7 years. The three other systems with an average CUC of 82.4% and of the DU_{LQ} of 80.7% were approximately 13.7 years old. There was really not any observed relationship between longevity and performance of the system as the oldest system (System J at 20 years) had a CUC of 92.7 and DU_{LQ} of 91.3% during 2008. These results agree well with other published studies that system longevity is a poor indicator of SDI system performance (Hanson et al., 1995; Pitts et al., 1996).

Table 2.a. 2008 results for the performance evaluation of ten older SDI systems in West Texas.

Site	Years since installation	Dripline pressure kPa (PSI)	Measured emitter flowrate L h^{-1} (GPH)	Design emitter flowrate L h^{-1} (GPH)	Emitter spacing cm (inches)	CUC (%)	DU_{LQ} (%)
A	11	52 (7.5)	0.79 (0.21)	0.91 (0.24)	60 (24)	89.0	87.9
B	8	103 (15.0)	0.79 (0.21)	0.61 (0.16)	60 (24)	92.2	93.0
C	10	124 (18.0)	1.14 (0.30)	0.76 (0.20)	60 (24)	92.1	91.1
D	12	55 (8.0)	1.14 (0.30)	1.51 (0.40)	76 (30)	91.7	91.6
E	11	83 (12.0)	0.91 (0.24)	0.76 (0.20)	60 (24)	84.8	79.4
F	9	38 (5.5)	0.49 (0.13)	0.61 (0.16)	60 (24)	90.3	86.6
G	10	34 (5.0)	0.95 (0.25)	0.76 (0.20)	60 (24)	94.3	92.3
H	15	45 (6.5)	0.79 (0.21)	1.51 (0.40)	76 (30)	83.2	83.4
I	15	24 (3.5)	0.83 (0.22)	1.51 (0.40)	76 (30)	79.3	79.2
J	20	41 (6.0)	0.38 (0.10)	0.56 (0.15)	30 (12)	92.7	91.3

During 2009, System P had the least DU_{LQ} (57.2%) and least CUC (27.2%). System M also presented a low DU_{LQ} (61.8%) and low CUC (27.2%). System P was operated under adequate pressure, but system L was being operated under very low pressure (22 KPa or 3.2 PSI). In both systems phosphoric acid was injected. It is probable that the low uniformity of system "L" could be caused by a low operating pressure. The reasons for the low uniformity of system "P" will be explained by the assessment of the maintenance practices in the following section.

Table 2.b. 2009 results for the performance evaluation of ten older SDI systems in West Texas.

Site	Years since installation	Dripline pressure kPa (PSI)	Measured emitter flowrate L h^{-1} (GPH)	Design emitter flowrate L h^{-1} (GPH)	Emitter spacing cm (inches)	CUC (%)	DU_{LQ} (%)
K	10	68 (9.9)	0.95 (0.25)	0.87 (0.23)	76 (30)	91.9	91.9
L	9	61 (8.8)	0.91 (0.24)	0.87 (0.23)	76 (30)	89.8	87.7
M	10	22 (3.2)	0.58 (0.15)	0.87 (0.23)	60 (24)	61.8	47.8
N	6	118 (17.1)	0.78 (0.21)	0.61 (0.16)	60 (24)	71.0	81.6
O	9	76 (11.0)	0.90 (0.24)	0.87 (0.23)	76 (30)	84.0	81.5
P	9	99 (14.4)	0.86 (0.23)	0.87 (0.23)	76 (30)	57.2	27.2
Q	12	62 (9.0)	0.98 (0.25)	0.87 (0.23)	76 (30)	92.6	90.0
R	10	47 (6.8)	0.88 (0.23)	1.87 (0.23)	76 (30)	95.5	94.3

Table 3.a. 2008 Dripline brand and model names, dripline size (ID), and fertilizers sources for the ten older SDI systems that were evaluated in West Texas.

Site	Dripline brandname	Dripline Size mm (inches)	Nitrogen fertilizer	Phosphorus fertilizer
A	Netafim Python	22 (0.785)	32-0-0 / N-pHuric	Phosphoric Acid
B	Netafim Python	22 (0.785)	32-0-0	Phosphoric Acid
C	Netafim Python	22 (0.785)	32-0-0	Miller Solugro
D	Netafim Python	22 (0.785)	32-0-0	None
E	Netafim Python	22 (0.785)	32-0-0	None
F	Netafim Python	22 (0.785)	32-0-0	None
G	Netafim Python	22 (0.785)	32-0-0	Phosphoric Acid
H	Netafim Python	20 (0.800)	32-0-0	None
I	Netafim Python	20 (0.800)	32-0-0	None
J	Chapin	16 (0.625)	32-0-0	None

Table 3.b. 2009 dripline brand and model names, dripline size (ID), and fertilizers sources for the eight older SDI systems that were evaluated in West Texas.

Site	Dripline Brandname	Dripline Size mm (inches)	Nitrogen fertilizer	Phosphorus fertilizer
K	Netafim Python	22 (0.875)	32-0-0	None
L	Netafim Python	22 (0.875)	32-0-0	Phosphoric Acid
M	Netafim Python	22 (0.875)	32-0-0	None
N	Netafim Python	25 (1.00)	32-0-0	12-48-08 Solugro humic acid & calcium sulfate
O	Netafim Python	22 (0.875)	32-0-0	None
P	Netafim Python	22 (0.875)	32-0-0	Phosphoric Acid
Q	Netafim Python	22 (0.875)	32-0-0	None
R	Netafim Python	22 (0.875)	32-0-0	None

Maintenance Programs

The most common maintenance practices were flushing of the filters, periodic flushing of manifolds and periodic injections of chlorine and sulfuric acid. Most of the farmers flushed the filters daily, except for three farmers that flushed every two days (two systems in 2008 and one in 2009) [Table 4a and 4b]. The filter flushing time varied from 1 to 1.66 minutes. The manifolds were generally flushed once a year, although three farmers did it once every two years and another once every three years. The most common chemical injections were chlorine and sulfuric acid. There was a great variability in the chlorine injection practices. Some farmers have never injected chlorine and three injected every other year. Two other farmers injected the chlorine after 7 and 8 years of use. Farmer P, who had the least DU_{LQ} (57.2%) and least CUC (27.2%) had not injected chlorine in his 9 years-old system which may help explain the clogging of the emitters. Two farmers injected chlorine after every 40 cm of water applied, and stopped the injection, once the strip paper indicated free chlorine of 10 mg/L. The chlorine used was Univar's sodium hypochlorite, which is 12% concentration. They apply it at approximately 0.47 L/ ha (1/2 gallons for 10 acres). Most of the farmers injected the sulfuric acid by lowering the pH below 3.5 once a year, except farmer P. The sulfuric acid that most farmers use is 95% concentration and they apply it at approximately 0.94 L/ha^{-1} (1 gal/10 acres). One farmer injected N-pHuric instead of sulfuric acid.

Table 4.a. 2008 typical maintenance practices for the ten older SDI systems that were evaluated in West Texas as indicated by the producers.

Site	Filter flushing regimen		Manifold flushing	Chlorine injection	Sulfuric acid injection (interval and amount)
	Interval (hr)	Duration (min)			
A	24	1.50	Annual	Never	N-pHuric
B	24	1.33	Annual	Never	Annually lowering pH down to 3.0
C	24	2.00	Annual	Bi-annually	Annually lowering pH down to 2.0
D	48	2.50	Annual	First after 8 years	Annually lowering pH down to 3.5
E	48	2.50	Annual	First after 7 years	Annually lowering pH down to 3.5
F	24	1.00	Every 2 years	none	Every 2 years lowering pH down to 3.0
G	24	1.66	Every 3 years	Every 3 years	Every 3 years lowering pH down to 3.1
H	96	2.0	Twice per year	Every 16 inches of irrigation to concentration of 10 mg/L	Every 16 inches of irrigation lowering pH down to 3.0
I[1]	NA	NA	NA	NA	NA
J	48	4.0	Annual	Every 16 inches of irrigation to concentration of 10 mg/L	Every 16 inches of irrigation lowering pH down to 3.5

[1] Maintenance information for system I was not available (NA).

Table 4.b. 2009 typical maintenance practices for the ten older SDI systems that were evaluated in West Texas as indicated by the producers.

Site	Filter flushing regimen		Manifold flushing	Chlorine injection	Sulfuric acid injection (interval and amount)
	Interval (hr)	Duration (min)			
K	12	0.50	Once/Year	None for past 2 years	None for past 2 years
L	24	1.50	Once/Year	Annually to concentration of 10 mg/L	Annually lowering pH to 3.7
M	24	1.50	Every other year	Every 2 years to concentration of 20 mg/L	Every 2 years lowering pH to 3.5
N	48	0.67	Every other year	Annually	Annually lowering pH to 2.0
O	24	2.50	Once/Year	Every 2 years to concentration of 20 mg/L	Every 2 years lowering pH to 3.5
P	24	1.50	Once/Year	None	None
Q	48	1.50	Once/Year	One time to concentration of 20 mg/L	One time lowering pH to 3.5
R	24	0.67	Two times	Two times to concentration of 20 mg/L	Two times lowering pH down to 3.5

Summary and Conclusions

Ten older SDI systems that had been installed over 8 years ago were evaluated in 2008 and eight systems over 6 years old were evaluated in 2009 for emitter performance. The Christiansen's uniformity coefficient (CUC) for 2008 systems was greater than 79.3%. However, the uniformity was low for two of the systems evaluated in 2009 with CUC of 57.2 and 61.8%. No fully-clogged emitters were observed in the 2008 evaluated systems probably due to the good maintenance practices and the good water quality of the aquifer. One of the systems evaluated in 2009 had several clogged emitters because of the lack of chlorine and sulfuric injects. Another system evaluated in 2009 that had low uniformity was being operated under very low pressure (22 KPa). Most of the farmers flushed their sand filters every day or twice per day for at least one minute. Most of the farmers flushed their manifolds once a year and injected sulfuric acid to lower the pH of the water to less than 3.5 at least once a year to prevent or reduce emitter clogging. The injection of chlorine was highly variable from site to site, applied yearly, biannually, triennially or after seven or more years. The farmer that had the most clogging problems never injected chlorine.

Acknowledgements

[1] Mention of tradenames is for informational purposes only and does not constitute endorsement by the authors or by the institutions they serve.

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Effect of the Changing U.S. Economy on the Relative Profitability of Center Pivot Sprinklers and SDI Systems

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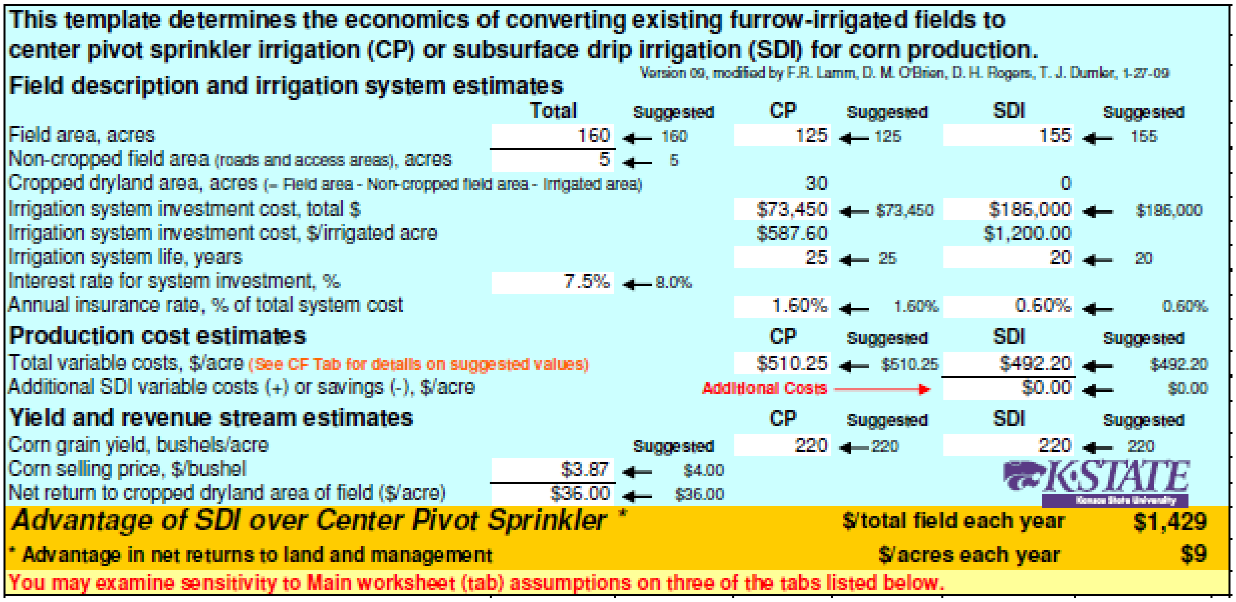
In much of the Great Plains, the rate of new irrigation development is slow or zero. Since the 1970s there has been a dramatic shift in irrigation methods in the Great Plains region, as center pivot sprinkler irrigation systems have become the predominant technology, having replaced much of the furrow- irrigated base. In addition, a small yet increasing amount of subsurface drip irrigation (SDI) has been installed. Although SDI systems represent less than 1 percent of the irrigated area, producer interest still remains high because of their greater irrigation efficiency and irrigated water application uniformity. As irrigation systems need to be upgraded or replaced, available irrigated water sources become more scarce, and farm sizes become larger, there will likely be a continued interest in and momentum toward conversion to modern pressurized irrigation systems.

Irrigation system investment decisions will be affected by both the physical characteristics of the irrigation systems being considered and the economic environment that irrigated crop enterprises are operating within. Key assumptions about the physical characteristics of the irrigation systems include input-output efficiencies, life span, and system investment costs. Key economic factors include commodity prices, costs of key crop inputs, irrigation energy costs, interest rates on operating expenses, the opportunity cost of capital investments, and overall inflation in production costs. The economic factors affecting irrigation system choices can be strongly influenced by broader macroeconomic conditions and trends in the United States and world economies. To the degree that the volatile patterns in agricultural, energy and financial markets since the early 1970s continue or even become more pronounced, economic decisions about irrigation system investments will become more risk-prone and uncertain.

This paper will discuss how volatile economic conditions in key agricultural and financial markets affect expected relative profitability of center pivot sprinkler and subsurface drip irrigation systems under crop production conditions in the Great Plains. This analysis will use a K-State center pivot sprinkler (CP) and subsurface drip irrigation (SDI) comparison spreadsheet (Lamm, et al., 2009) to estimate the affect of various key economic factors upon investment decisions.

CP-SDI Comparison Spreadsheet

K-State Research and Extension introduced a free Microsoft Excel[1] spreadsheet template for making economic comparisons of CP and SDI in the spring of 2002. The spreadsheet has been periodically updated since that time to reflect changes in input data, particularly system and corn production costs. The spreadsheet also provides sensitivity analyses for key factors. Lamm, et al., (2009) explains how to use the spreadsheet and the key factors that most strongly affect the returns comparisons. The online accessible template has five worksheets (tabs), the Main, CF, Field size & SDI life, SDI cost & life, Yield & Price tabs. Most of the calculations and the result are shown on the Main tab (Figure 1.). Critical field and irrigation system assumptions are illustrated.



This template determines the economics of converting existing furrow-irrigated fields to center pivot sprinkler irrigation (CP) or subsurface drip irrigation (SDI) for corn production.

Version 09, modified by F.R. Lamm, D. M. O'Brien, D. H. Rogers, T. J. Dumler, 1-27-09

Field description and irrigation system estimates	Total	Suggested	CP	Suggested	SDI	Suggested
Field area, acres	160	← 160	125	← 125	155	← 155
Non-cropped field area (roads and access areas), acres	5	← 5				
Cropped dryland area, acres (= Field area - Non-cropped field area - Irrigated area)			30		0	
Irrigation system investment cost, total $			$73,450	← $73,450	$186,000	← $186,000
Irrigation system investment cost, $/irrigated acre			$587.60		$1,200.00	
Irrigation system life, years			25	← 25	20	← 20
Interest rate for system investment, %	7.5%	← 8.0%				
Annual insurance rate, % of total system cost			1.60%	← 1.60%	0.60%	← 0.60%
Production cost estimates			CP	Suggested	SDI	Suggested
Total variable costs, $/acre (See CF Tab for details on suggested values)			$510.25	← $510.25	$492.20	← $492.20
Additional SDI variable costs (+) or savings (-), $/acre			Additional Costs →		$0.00	← $0.00
Yield and revenue stream estimates			CP	Suggested	SDI	Suggested
Corn grain yield, bushels/acre		Suggested	220	← 220	220	← 220
Corn selling price, $/bushel	$3.87	← $4.00				
Net return to cropped dryland area of field ($/acre)	$36.00	← $36.00				

Advantage of SDI over Center Pivot Sprinkler *	**$/total field each year**	**$1,429**
*** Advantage in net returns to land and management**	**$/acres each year**	**$9**

You may examine sensitivity to Main worksheet (tab) assumptions on three of the tabs listed below.

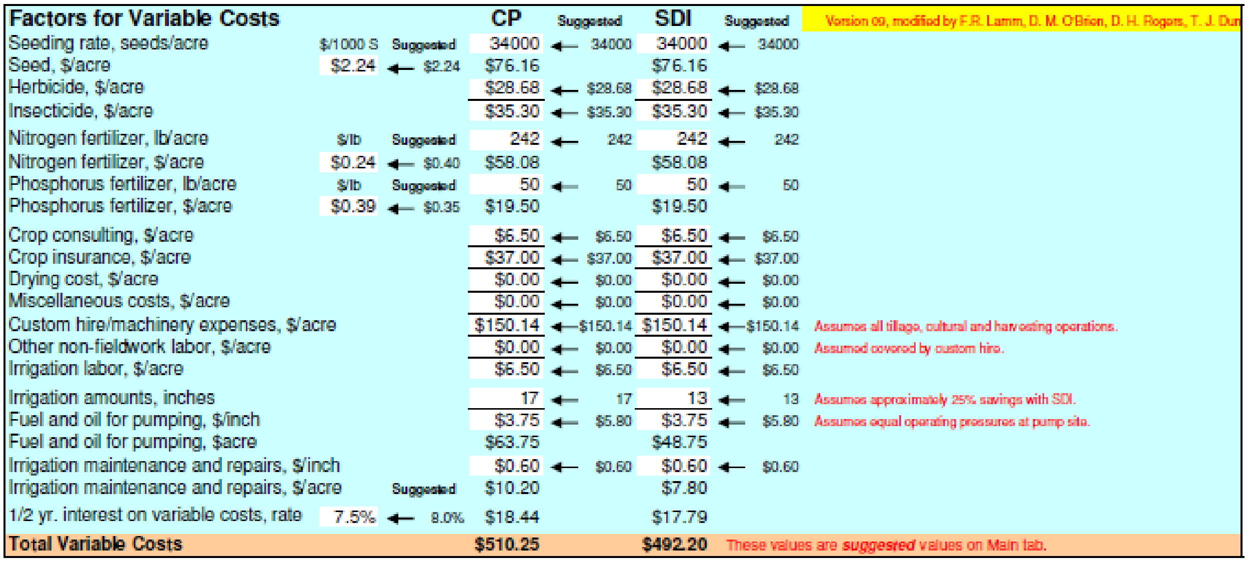
Figure 1. Main worksheet (tab) of the economic comparison spreadsheet template indicating the 18 required variables (white input cells) and their suggested values when further information is lacking or uncertain.

The scenario analyzed in this research is a comparison of whether a center pivot sprinkler irrigation system (CP) is more or less profitable than a subsurface drip irrigation system on 160 acres of farmland. The CP system would irrigate 125 acres of the 160 acres of farmland, with the remaining 35 acres divided between 30 acres of non-irrigated or "dryland" cropping systems and 5 acres of non-cropped area (i.e., roads and access areas). The SDI system would irrigate 155 acres of the 160 acres of farmland, with the remaining 5 acres used for non-cropped roads and access areas. Irrigation system design and cost information is available from the authors and the K-State Research and Extension publication <u>Irrigation Capital Requirements and Capital Costs</u>, MF-836. Only information that is relevant to the comparison of returns for CP and SDI systems is included in this analysis. This excludes such factors as cost of irrigated cropland which will not vary for those acres that are irrigated under either irrigation system investment scenario. Non-irrigated cropland returns are included because of the inclusion of dryland acreage under the CP scenario. Average cash rental rates are included as a market-based proxy for the returns expected from farming non-irrigated cropland. For further discussion of the assumptions used in this analysis see Lamm, et al. (2009).

Actual values used in this analysis may vary from suggested values in the Main tab of the worksheet where current prices and market conditions warrant. Key information from the Main tab for the following analysis is as follows.

1. Corn selling price, $/bushel = $ 3.87 /bushel
2. Interest rate for system investment, % = 7.5%
3. Total variable costs, $/acre: CP = $510.25
4. Total variable costs, $/acre: SDI = $492.20
5. Net return to cropped dryland area of field ($/acre) = $ 36.00

Production cost estimates and assumptions represented in the CF tab are based on K-State Research and Extension crop enterprise budget estimates for irrigated corn in western Kansas (Figure 2.).



Factors for Variable Costs				**CP**		Suggested	**SDI**		Suggested	Version 09, modified by F.R. Lamm, D. M. O'Brien, D. H. Rogers, T. J. Dun
Seeding rate, seeds/acre	$/1000 S		Suggested	34000	←	34000	34000	←	34000	
Seed, $/acre	$2.24	←	$2.24	$76.16			$76.16			
Herbicide, $/acre				$28.68	←	$28.68	$28.68	←	$28.68	
Insecticide, $/acre				$35.30	←	$35.30	$35.30	←	$35.30	
Nitrogen fertilizer, lb/acre	$/lb		Suggested	242	←	242	242	←	242	
Nitrogen fertilizer, $/acre	$0.24	←	$0.40	$58.08			$58.08			
Phosphorus fertilizer, lb/acre	$/lb		Suggested	50	←	50	50	←	50	
Phosphorus fertilizer, $/acre	$0.39	←	$0.35	$19.50			$19.50			
Crop consulting, $/acre				$6.50	←	$6.50	$6.50	←	$6.50	
Crop insurance, $/acre				$37.00	←	$37.00	$37.00	←	$37.00	
Drying cost, $/acre				$0.00	←	$0.00	$0.00	←	$0.00	
Miscellaneous costs, $/acre				$0.00	←	$0.00	$0.00	←	$0.00	
Custom hire/machinery expenses, $/acre				$150.14	←	$150.14	$150.14	←	$150.14	Assumes all tillage, cultural and harvesting operations.
Other non-fieldwork labor, $/acre				$0.00	←	$0.00	$0.00	←	$0.00	Assumed covered by custom hire.
Irrigation labor, $/acre				$6.50	←	$6.50	$6.50	←	$6.50	
Irrigation amounts, inches				17	←	17	13	←	13	Assumes approximately 25% savings with SDI.
Fuel and oil for pumping, $/inch				$3.75	←	$5.80	$3.75	←	$5.80	Assumes equal operating pressures at pump site.
Fuel and oil for pumping, $acre				$63.75			$48.75			
Irrigation maintenance and repairs, $/inch				$0.60	←	$0.60	$0.60	←	$0.60	
Irrigation maintenance and repairs, $/acre			Suggested	$10.20			$7.80			
1/2 yr. interest on variable costs, rate	7.5%	←	9.0%	$18.44			$17.79			
Total Variable Costs				**$510.25**			**$492.20**			These values are *suggesred* values on Main tab.

Figure 2. CF worksheet (tab) of the economic comparison spreadsheet template and the current production cost variables. Sums at the bottom of the CF worksheet are the suggested values for total variable costs on the Main worksheet (tab).

Corn enterprise cost of production information is available from the authors and the K-State Research and Extension publication Center Pivot Irrigated Corn Cost Return Budget in Western Kansas, MF-585. Actual values may vary from suggested values in the worksheet where current prices and market conditions warrant.

Key assumptions represented on the CF tab that are relevant to this economic analysis are listed below.

1. Nitrogen fertilizer, \$/pound of 82-0-0 = \$ 0.24 /pound
2. Phosphorus fertilizer, \$/pound of 18-46-0 = \$ 0.39 /pound
3. Fuel and oil for pumping, \$/acre inch = \$ 3.75 /acre inch
4. ½ yr. Interest on variable costs, rate = 7.5% interest
5. Total variable costs, \$/acre: CP = \$510.25
6. Total variable costs, \$/acre: SDI = \$492.20

Lamm, et al. (2009) provides a further explanation of sensitivity analysis of physical production factors critical to the CP versus SDI investment decision in spreadsheet tabs on a) Field size & SDI life, b) SDI cost & life, and c) Yield & Price tabs.

Economic Factors Affecting CP versus SDI Investments

The key economic factors in this decision framework which are hypothesized to have an impact upon CP versus SDI investments include commodity prices, costs of key crop inputs, irrigation energy costs, interest rates on operating expenses, the opportunity cost of capital investments, and overall inflation in production costs.

Economic analysis typically relies upon “ceteris paribus” assumptions to determine the marginal impact of any particular factor in isolation (i.e., with "all other things being equal or held constant"). The following analysis will first focus on the impacts of variability of key factors separately (i.e., “ceteris paribus”). A final broader analysis will be conducted in which “low” versus “high” market product price and production cost regimes are examined to understand the systematic impact of these key factors. This systematic perspective reflects the integrated, interdependent nature of agricultural, energy and financial markets.

Corn Price Variability Impact

Over the July 2000-September 2009 period U.S. corn prices have exhibited great variability, with corn upfront corn futures contract prices ranging from approximately \$1.90 to \$7.50 per bushel (Figure 3.). In this analysis, CP versus SDI investment returns will be analyzed for the base budget corn price (\$3.87 per bushel), a low price (\$1.95) and a high price (\$6.00). The low price of \$1.95 per bushel represents the current U.S. average commodity marketing loan program price for corn. The high price of \$6.00 per bushel represents a basis-adjusted estimate of cash prices that would be typically available to crop producers at the high end of the 2000-2009 corn futures trading range.

Figure 3. CBOT Corn Futures Continuation Chart: July 2000-September 2009. Online source: www.futures.tradingcharts.com

In this analysis, lower corn prices tended to favor CP systems, while higher corn prices tended to favor SDI systems (Table 1). These results can also be derived from the Yield and Price tab of the K-State spreadsheet.

Table 1. Corn Price Variation Impact on SDI versus CP Returns

Corn Price Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: $3.87 per bu.	$510.25	$492.20	$1,429	$9
Low: $1.95 per bu.	$510.25	$492.20	**-$11,243**	**-$70**
High: $6.00 per bu.	$510.25	$492.20	$15,487	$97

Natural Gas – Pumping Cost Variability Impact

Just as for other agricultural and energy-related commodities, over the July 2000-September 2009 period U.S. natural gas prices have exhibited great variability. Lead contract natural gas futures contract prices have ranged from approximately $2.00 to nearly $16.00 per mcf. (Figure 4.).

In the irrigated crop enterprise budgets developed by K-State Research and Extension, natural gas is the energy source used to calculate irrigation pumping costs. Center pivot sprinkler versus SDI investment returns will be analyzed for a base budget natural gas price of $5.53 per mcf., leading to a cost of $3.75 per acre inch of water applied for pumping-related fuel and oil. The low natural gas price to be considered is $2.00 per mcf., leading to a cost of $1.55 per acre inch of water applied for pumping-related fuel and oil. The high natural gas price is $12.00 per mcf., leading to a cost of $7.78 per acre inch of water applied for pumping-related fuel and oil.

Figure 4. NYMEX Natural Gas Futures Continuation Chart: July 2000-September 2009. Online source: www.futures.tradingcharts.com

Natural gas price variation does not have a large impact on net returns in this analysis, causing a variation of $2 to $3 per acre in the advantage of SDI over CP systems from the base scenario (Table 2.).

Table 2. Natural Gas Price Variation Impact on SDI versus CP Returns

Natural Gas Price Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: $5.53 per mcf. 3.75 per acre inch	$510.25	$492.20	$1,429	$9
Low: $2.00 per mcf. 1.55 per acre inch	$471.45	$462.53	$1,178	$7
High: $12.00 / mcf. 7.78 per acre inch	$581.33	$546.56	$1,888	$12

Nitrogen and Phosphorous Fertilizer Cost Variability Impact

Fertilizer prices for anhydrous ammonia or NH3 (82-0-0 N-P-K) and di-ammonium phosphate or DAP (18-46-0 N-P-K) have also been extremely variable in the most recent decade. Over the 1999-2008 period U.S. fertilizer prices have trended higher, with 82-0-0 prices ranging from $211 to $755 per ton of nitrogen on average per year. During the summer of 2008 anhydrous ammonia prices reached over $1,050 per ton of nitrogen. During 1999-2008 di-ammonium phosphate prices ranged from $227 to $850 per ton, reaching up to $1,200 per ton in the summer months of 2008.

Although the prices for these two fertilizer products are not perfectly correlated, the low and high price scenarios for anhydrous ammonia and di-ammonium phosphate will be analyzed together. The base 82-0-0 price is $400 per ton or $0.24 per pound of nitrogen, and the base price for 18-46-0 is $0.39 per pound. The low 82-0-0 price is $211 per ton or $0.13 per pound of nitrogen, and $0.11 per pound for 18-46-0. The high 82-0-0 price is $950 per ton or $0.57 per pound of nitrogen, and $0.85 per pound for 18-46-0.

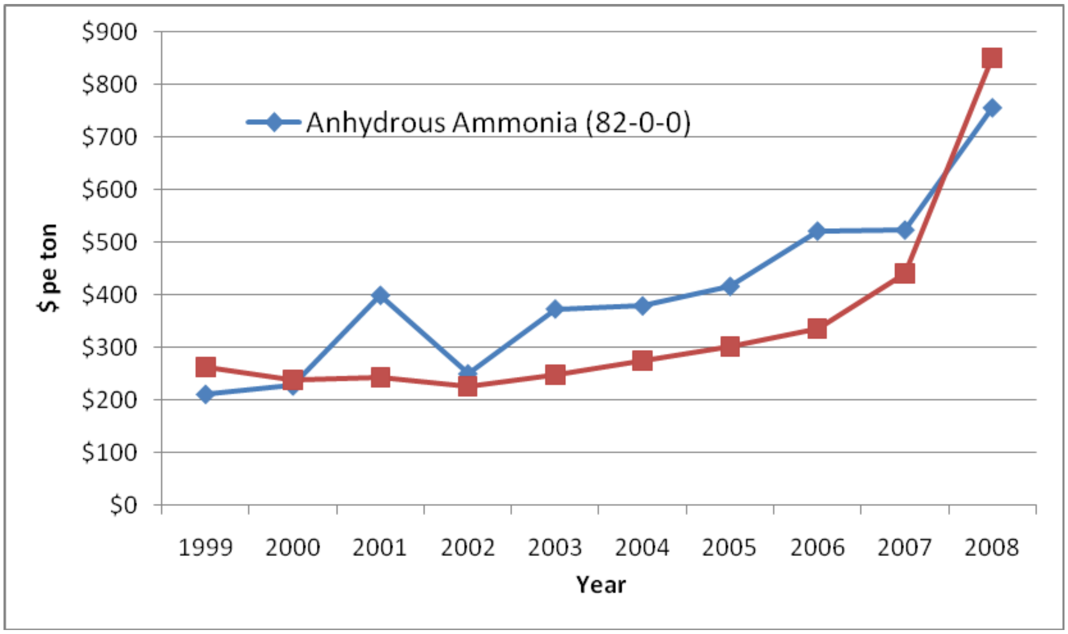


Figure 5. United States Annual Average Fertilizer Prices: 1999-2008. Source: USDA Economic Research Service

Fertilizer price variation does not have a large impact on net returns in this analysis, causing a variation of only $2 to $8 per acre in the advantage of SDI over CP systems from the base scenario (Table 3.).

Table 3. Fertilizer Price Variation Impact on SDI versus CP Returns

Fertilizer Price Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: $0.24 / lb 82-0-0 $0.39 / lb 18-46-0	$510.25	$492.20	$1,429	$9
Low: $0.13 / lb 82-0-0 $0.11 / lb 18-46-0	$467.93	$449.88	$2.698	$17
High: $0.37 / lb 82-0-0 $0.85 / lb 18-46-0	$616.97	$598.92	$1,773	$11

Interest Rate Variability Impact

Interest rates in the United States have varied from almost 0% up to 20% since 1950 (Figure 6.). Large swings in interest rates can have sizable impacts on the cost of borrowing money. In this analysis interest rates affect variable operating costs and the cost of borrowing money for irrigation system investments. Even if irrigation investments are paid for without credit and associated interest expenses on borrowed money, the opportunity cost of having capital invested in one enterprise as opposed to another are relevant to an investor's decision.

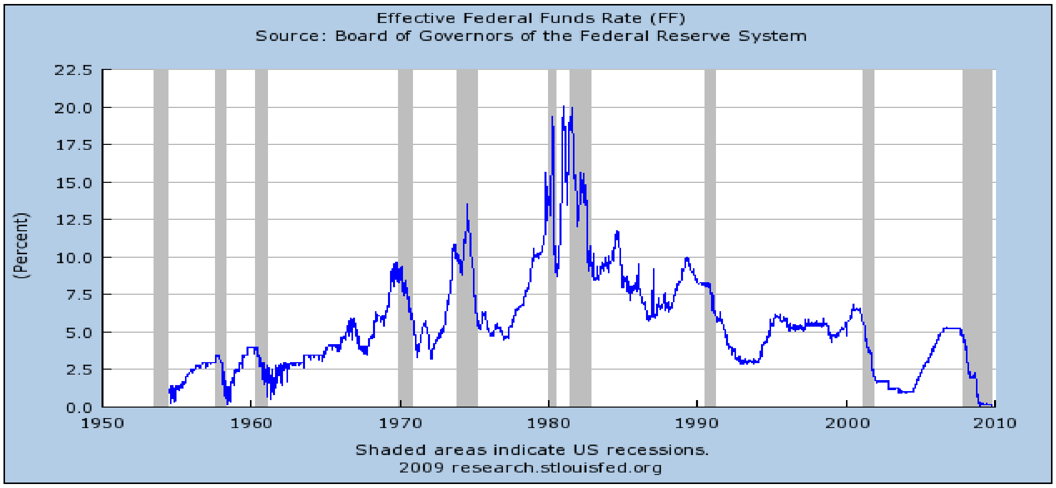


Figure 6. United States Interest Rates: 1950-2009. Source: St. Louis Federal Reserve Bank.

In this analysis the base interest rate used is 7.5%. The low interest rate scenario is calculated using a 5% rate on operating funds and capital investments. The high interest rate was set equal to the top rate charged during the period of the late 1980s – early 1990s, i.e., 20%.

Interest variation does have a large impact on relative returns in this analysis. Low interest rates near 5% benefit SDI over CP systems by $10 per acre, while historically high 20% interest rates cause CP systems to become more profitable than SDI systems by approximately $40 per acre (Table 4.).

Table 4. Interest Rate Variation Impact on SDI versus CP Returns

Interest Rate Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: 7.5% Interest	$510.25	$492.20	$1,429	$9
Low: 5.0% Interest	$504.11	$486.27	$2,987	$19
High: 20.0% Interest	$540.99	$521.85	**-$6,359)**	**-$40**

Cost Inflation Variability Impact

Since the early 1900s, inflation rates in the United States have varied from a negative 1.94% (i.e., deflation) during 1920-29 to a positive 8.7% during the 1913-1919 period (Figure 7.). Since World War II, the decade of the 1970s had the highest annual average rate of inflation at 7.09% per year. Periods of high inflation in the cost of consumer goods raise consumer's cost of living and tend to diminish their real inflation-adjusted buying power and personal wealth. In the same way, inflation in agricultural production costs tend to increase cost of production and diminish crop enterprise profitability if not accompanied by increases in agricultural product prices.

In this analysis, the impacts of one time inflations of 3% and 9% in the level of crop production costs are analyzed in comparison to the base scenario of no differential cost inflation. For this scenario, the impact of inflation in seed, herbicide, insecticide, crop consulting, crop insurance, custom hire / machinery expenses, labor costs, irrigation maintenance and repair, and non-irrigated cropland rental rates are examined. A more thorough multi-period analysis of inflation impacts over time is called for in future research.

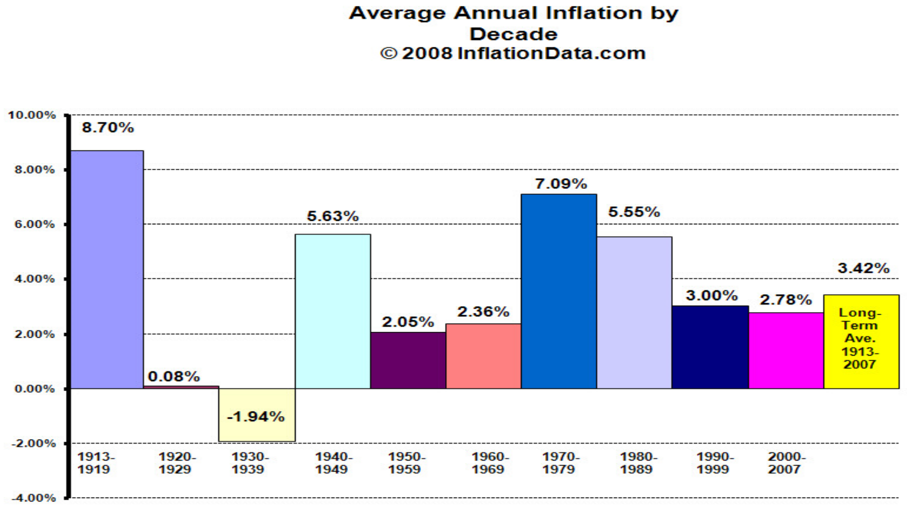


Figure 7. United States Inflation Rates by Decade: 1913-2007. Source: www.InflationData.com.

Inflation variation does not have a large impact on net returns in this analysis, causing declines of $2 to $7 per acre in the advantage of SDI over CP systems from the base scenario (Table 6.).

Table 6. Interest Rate Variation Impact on SDI versus CP Returns

Inflation Rate Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
Base: 0% Inflation	$510.25	$492.20	$1,429	$9
Low: 3% Inflation	$521.30	$503.17	$1,077	$7
High: 9% Inflation	$542.98	$524.70	$385	$2

Broader "Low versus High" Price Cost Scenario Impact

Given the interrelated nature of agricultural and financial markets, it is judicious to examine the impact of broader "low price-low cost" and "high price-high cost" scenarios upon the profitability of SDI versus CP systems. The various inputs into these two scenarios are given in Table 7.

Table 7. "Low" and "High" Price-Cost Scenario Inputs

Key Crop Inputs	"Low" Price-Cost Scenario	"High" Price-Cost Scenario
1. Corn Price, $/ bu.	$1.95	$6.00
2a. Natural Gas $, $/mcf.	$2.00	$12.00
2b. Pumping Cost, $/acre in.	$1.55	$7.78
3. Fertilizer Cost		
NH3 (82-0-0), $/lb. N.	$0.13	$0.37
DAP (18-46-0), $/lb.	$0.11	$0.85
4. Interest Rates	5.0%	20.0%
5. Inflation Rate in Crop Production Costs	3.0%	9.0%

Whether the “low” price – cost or the “high” price – cost regime is in effect has a large impact on the relative returns of an subsurface drip irrigation as opposed to a center pivot sprinkler irrigation system. “Low” prices and costs strongly favor CP systems while “high” price – cost scenarios strongly favor SDI systems (Table 8.).

Table 8. Interest Rate Variation Impact on SDI versus CP Returns

Inflation Rate Scenarios	CP Variable Cost ($ per acre)	SDI Variable Cost ($ per acre)	SDI Less CP Returns ($ per 160 acres)	SDI Less CP Returns ($ per acre)
“Low” Price - Cost Scenario	$434.88	$425.98	**-$9,026**	**-$56**
“High” Price - Cost Scenario	$764.20	$727.09	$3,691	$23

Summary and Conclusions

Variability in United States’ agricultural and financial markets impacts irrigation investment decisions in general, and the decision to purchase a center pivot sprinkler or subsurface drip irrigation system in particular. The levels of economic variability observed in U.S. grain, energy, crop input and financial markets have been particularly heightened in recent years. If the recent past is a reasonable predictor of the future, then volatility in these markets is likely to add risk and uncertainty to irrigation investment decisions for the foreseeable future.

This analysis was based on a decision tool developed by Kansas State University to assist farmers in their irrigation system investment decisions – particularly as they consider whether to invest in center pivot sprinkler or subsurface drip irrigation systems. This analysis focused on the impact of broader economic factors whereas earlier efforts (Lamm, et al, 2009) focused more so on system physical efficiencies, design and life span in determining the most profitable system investment.

These results indicate that economic factors and forces that tend to either increase irrigated crop income or that tend to increase costs equally between the irrigation system alternatives tend to either favor subsurface drip irrigation or are neutral to the investment decision between the two options. Higher corn prices distinctly favor subsurface drip irrigation system returns, while lower corn prices favor center pivot irrigation systems. Changes in fertilizer prices, natural gas prices and associated irrigation pumping costs, and inflation in crop production costs tend to have neutral or small impacts upon the relative returns to each irrigation system.

Because of the higher investment cost required for subsurface drip irrigation systems, increases in interest rates on either borrowed capital or the on the opportunity cost of invested capital in irrigation systems tend to favor investment in center pivot sprinkler irrigation systems with their lower costs of initial investment.

When grouping economic factors into “low price – cost” and “high price – cost” scenarios, it turns out that “low price – cost” scenarios tend to favor center pivot sprinkler irrigation cost investments. Conversely, “high price – cost” scenarios of economic factors favors subsurface drip irrigation investments.

Future analysis should focus on the multi-period impacts of inflation, interest, and variability in product revenues and crop input costs. If farmers believe the hypothesis that higher levels of volatility will continue to exist in agricultural, energy and financial markets in the future, then their irrigation investment decisions will need to be all that much more informed in regards to the physical and economic uncertainties they are dealing with.

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Contribution No. 10-113-A from the Kansas Agricultural Experiment Station.

This paper is also part of a year-long SDI technology transfer effort in 2009 involving Kansas State University, Texas A&M University and the USDA-ARS and is funded by the Ogallala Aquifer Project. To follow other activities of this educational effort, point your web browser to http://www.ksre.ksu.edu/sdi/. Watch for this logo.

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Importance of Reclaimed Water in Florida

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Abstract. *Florida is the largest producer of reclaimed water in the U.S., and this water has become an important alternate water source for Florida. The purpose of this paper is to discuss several issues related to reclaimed water use in Florida. While agriculture was initially the largest user of reclaimed water, golf courses and landscape irrigation are now its largest users. Initially, growers refused to accept reclaimed water because of concerns over salinity, heavy metals, and potential disease organisms. These fears were proved to be unfounded, and most citrus growers and residential users now accept reclaimed water. Studies have shown that reclaimed water promotes excellent citrus tree growth. Reclaimed water has an excellent safety record, and has been used successfully in Florida for more than 40 years with no reported incidents of illness. While citrus trees can extract adequate amounts of some micronutrients, they are not able to take up sufficient nitrogen from reclaimed water. Hence, fertilization is still necessary when using reclaimed water. While not usually a problem, salinity can sometimes be an issue in coastal areas. Periodic droughts since 2000 and fewer restrictions on reclaimed water for irrigation have increased demand for this water. Reclaimed water has become an important source to help meet growing urban water needs. With increasing population, reclaimed water will continue to play a significant role in overall Florida water management.*

Keywords. Recycled water, irrigation, reuse, wastewater

Introduction

Florida has less than half the population of California. Statewide, Florida receives an average of 54 inches of rainfall, while much of southern California receives less than half that amount. Yet Florida is the leading state in the nation in terms of reclaimed water production. Why is this?

Issues relating to water quality, population growth, and saltwater intrusion are some of the primary reasons that Florida currently produces more reclaimed water than other states. Florida's population increased five-fold from 1950 to 2000, and it is now the fourth largest state in the nation with a 2008 estimated population of 18.3 million.

Several major reclaimed water projects in Florida were started for water quality reasons. The City of St. Petersburg developed its reclaimed water system in 1972 after passage of the Wilson-Grizzle Act. This act mandated that "wastewater treatment plants discharging to Tampa Bay and its tributaries treat their wastewater to that of drinking water standards…" (Tchobanoglous et al., 2003). St. Petersburg became the first major city in the U.S. to reach zero discharge of wastewater effluent into nearby surface waters. By reducing demand for well water near the coast, this project helped slow saltwater intrusion. Another project, Water Conserv II, was started in 1986 to stop discharge of treated wastewater from Orlando and Orange County into Lake Tohopekaliga, an important recreational bass-fishing lake. Now, water shortages (or lack of water quantity) in Florida are helping drive the increased production of reclaimed water.

Recent spring droughts from 2000 through 2009 have increased demand for reclaimed water. Severe restrictions were placed on residential irrigation with potable water in Tampa in 2009, while there were fewer restrictions on reclaimed water irrigation. Most of the Water Management Districts in Florida are actively promoting the use of reclaimed water as a way to save potable water.

Uses of Reclaimed Water

As of 2007, Florida produced an estimated 242.1 billion gallons of reclaimed water per year. Current inventory data on California could not be found, but estimated reclaimed water production in California in 2002 was 171.22 billion gallons (Fig. 1). Production of reclaimed water in Texas was 40.96 billion gallons in 2003 and is estimated to increase to 141.57 billion gallons by 2010.

In 1992, Florida produced 290 million gallons of reclaimed water per day (mgd) and this more than doubled to 663.3 mgd by 2007 (FDEP, 2009). In 1992, agriculture was the largest user of reclaimed water in Florida and golf course irrigation was the second largest user. By 2007, Florida agriculture used only 12% while golf courses used 21% of the total reclaimed water (Fig. 2). In contrast, agriculture was still the dominant user of recycled water in 2002 in California (Fig. 2) and accounted for 46% of the total recycled water use.

The U.S. Environmental Protection Agency (EPA) established guidelines for water reuse. Rather than establishing national water reuse standards, the EPA decided that comprehensive federal guidelines, along with state regulations, would increase implementation of water reuse projects. Hence, states have established their own water reuse regulations.

In Florida, the Florida Department of Environmental Protection (FDEP) established these water quality standards and regulates reclaimed water. Florida has been a leader in the production and use of reclaimed water for several decades.

Reclaimed water helps extend water supplies and helps meet Florida’s growing demand for water. Reclaimed water is used for many purposes in Florida, including the following:

- Lawn and landscape irrigation;
- Water for decorative fountains, lakes, or ponds;
- Industrial uses, such as cooling towers;

- Wetlands restoration or enhancement;
- Irrigation of edible crops (citrus and vegetable) that will be peeled or cooked before eating; and
- Indirect irrigation of edible crops that will not be peeled or cooked (by using drip or other forms of irrigation where there is no direct contact of the reclaimed water with the edible part of the plant).

Although reclaimed water meets more than 95% of drinking water standards, reclaimed water is not intended to be used for drinking. Hence, in Florida, reclaimed water cannot be used for the following purposes:

- Drinking or cooking;
- Filling swimming pools or hot tubs;
- Interconnecting with a drinking water pipeline; and
- Playing in water that involves continuous contact with reclaimed water (SWFWMD, 2009).

Safety of Reclaimed Water

Reclaimed water has an excellent safety record. Reclaimed water has been used in Florida for more than 40 years with no incidence of illness. Because reclaimed water is disinfected (usually by chlorination), it can be better than some other irrigation sources from a health-and-safety point of view. In fact, reclaimed water undergoes more testing than most irrigation waters. Water quality standards for reclaimed water are more strict than standards for recreational water. Because of these strict water quality standards, there is essentially no risk to humans or animals from periodic contact with reclaimed water.

Reclaimed water can meet drinking water standards for many elements, but reclaimed water is not required to meet all the drinking water standards. (Reclaimed water is not currently intended to be directly used for drinking.)

Irrigation of Edible Crops

For crops that are “peeled, cooked, or thermally processed,” reclaimed water can be directly applied to the edible part of the crop. Hence, reclaimed water can be used with overhead irrigation for citrus and other crops that are peeled or cooked.

For crops that are eaten raw (called the “salad crops”), FDEP regulations currently require that there be no direct contact of the reclaimed water with the edible part of the crop. This means that growers of salad crops who irrigate with reclaimed water should use drip, bubbler, or furrow irrigation, which does not spray water directly on the crop.

This regulation also means that reclaimed water cannot be used in Florida for overhead frost protection sprays onto crops such as blueberries or strawberries.

The regulation prohibiting direct contact of reclaimed water with salad crops was created in the 1980s to encourage acceptance of reclaimed water. At the time, there were not sufficient studies to determine whether such a precaution was necessary. Since then, studies conducted in California have shown that salad crops can be directly sprayed with reclaimed water with no health, safely, or marketing problems. This finding was expected because reclaimed water is disinfected, usually by chlorination. Sunshine is also a good disinfectant. Currently, reclaimed water can be sprayed onto the edible portion of salad crops in California, but this practice is not allowed by regulations in Florida.

Nutrients in Reclaimed Water

Reclaimed water contains small amounts of elements that are beneficial for plant growth, such as nitrogen, phosphorus, potassium, calcium, and magnesium. Reclaimed water can also contain low levels of other essential elements, such as manganese, zinc, and boron. Boron is an element that is essential for plant growth in small quantities, but it can cause plant damage if too much is applied.

Nutrient concentration in reclaimed water, particularly advanced treated reclaimed water, is usually low. Important macronutrients include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). For example, the concentrations of N, P, and K in some reclaimed water sources are less than 30, 10, and 30 mg/liter, respectively.

Along with other environmental factors, the amount of nutrient uptake from reclaimed water by plants depends on the concentration of nutrients, amount of reclaimed water applied, and residence time of the reclaimed water in the root zone. With regular irrigation, several turf grasses can extract some N and P from reclaimed water. In those cases, reclaimed water can supply a significant amount of these nutrients. With other crops such as citrus, commonly practiced irrigation with reclaimed water provides less than 16% of the normal nitrogen requirement for mature trees. While reclaimed water can provide some essential elements, the concentrations of N and K are usually too low to meet plant needs completely. Hence, additional applications of nitrogen, potassium, and other fertilizer elements are necessary to ensure good plant growth.

Salinity

When reclaimed water is created, the process can increase the salt concentration in the water. This increase in salts is usually not of great importance. However, in coastal areas, the incoming source water used to produce reclaimed water may already be salty. Also, the transmission pipes for the reclaimed water may go through areas of salty water. Additionally, as pipes age, they can develop cracks and leaks, which allow some outside water to penetrate the pipes. This process is called infiltration. If salty water infiltrates into the reclaimed water pipes, the level of salt in the reclaimed water can further increase.

In inland Florida locations, salt in reclaimed water is not usually a problem. However, in coastal regions, whether due to infiltration or the incoming water source, salts in reclaimed water can sometimes be a problem for salt-sensitive plants such as azaleas or Chinese privet. If salinity is too high, the reclaimed water may be acceptable for most lawn irrigation, but not for irrigation of salt-sensitive plants.

Some water reclamation facilities that produce reclaimed water monitor salts. If the salt concentration gets too high, they will reprocess or divert the salty reclaimed water to another discharge point.

Perception of Reclaimed Water

When using reclaimed water for irrigation was presented to citrus growers for the Water Conserv II project in the 1980s, they initially rejected the idea of using such water. Growers were concerned about possible tree damage due to heavy metals, salinity, disease organisms, or excessive water (Parsons et al., 2001a). After much negotiation, water quality standards were established and several growers decided to take a chance with the reclaimed water. At the request of growers, research was carried out on this water by scientists at the University of Florida. The research showed that excessive quantities of this water could be applied to citrus on well-drained soils with no negative effects (Parsons et al., 2001b). Tree growth and fruit production was greater at the high irrigation rate. Even though the concentration of soluble solids was lowered by the high irrigation rate, total soluble solids per acre were significantly higher due to the greater fruit production.

Quality standards of the reclaimed water were maintained, and more growers agreed to accept the water. Now, citrus growers that initially opposed the idea of using reclaimed water are enthusiastic supporters of this water. Nearly 800 parks and 477 golf courses are currently irrigated with reclaimed water (FDEP, 2009); and with fewer irrigation restrictions on reclaimed water, public acceptance has increased noticeably.

However, perception issues still exist. For example, many Florida tomato growers do not want to use reclaimed water because of perceived, but scientifically unfounded, concerns over food safety. This attitude developed because Florida tomato growers were economically hurt by a *Salmonella* incident. Because of a *Salmonella* outbreak, the Food and Drug Administration initially recommended that people not eat certain types of raw tomatoes in 2008. It was later found that tomatoes were not the source of *Salmonella*, but Florida growers lost an estimated $50 to $100 million because of the negative publicity. Even though reclaimed water has no association with *Salmonella*, Florida tomato growers are afraid to use it because of imagined issues related to food safety.

Conclusion

Reclaimed water use has increased steadily since the 1980s, and Florida is now the largest producer of this water in the U.S. This water has an excellent safety record and has been used successfully for more than 40 years. While reclaimed water in Florida was initially promoted to improve surface water quality, it has now become an important alternate source of water to help meet water shortages and urban demand.

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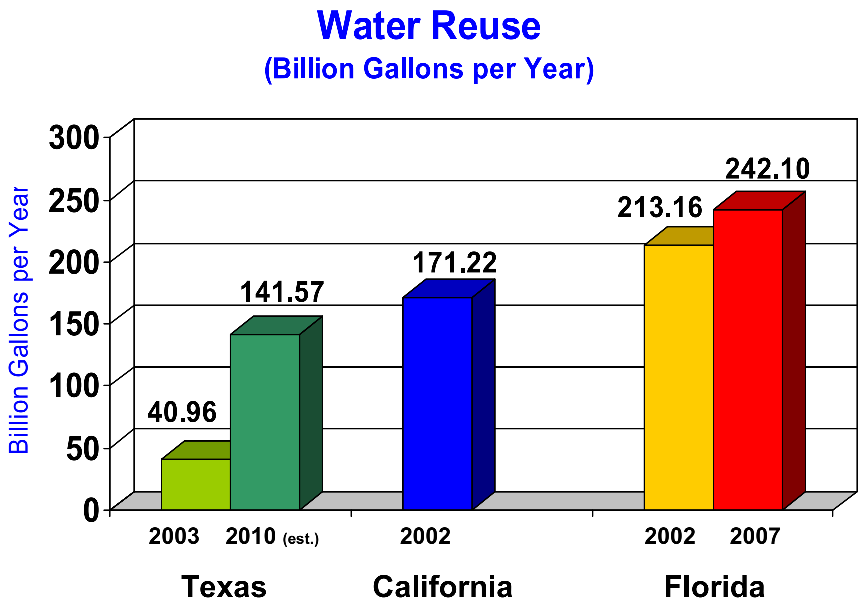

Figure 1. Water reuse in different states.

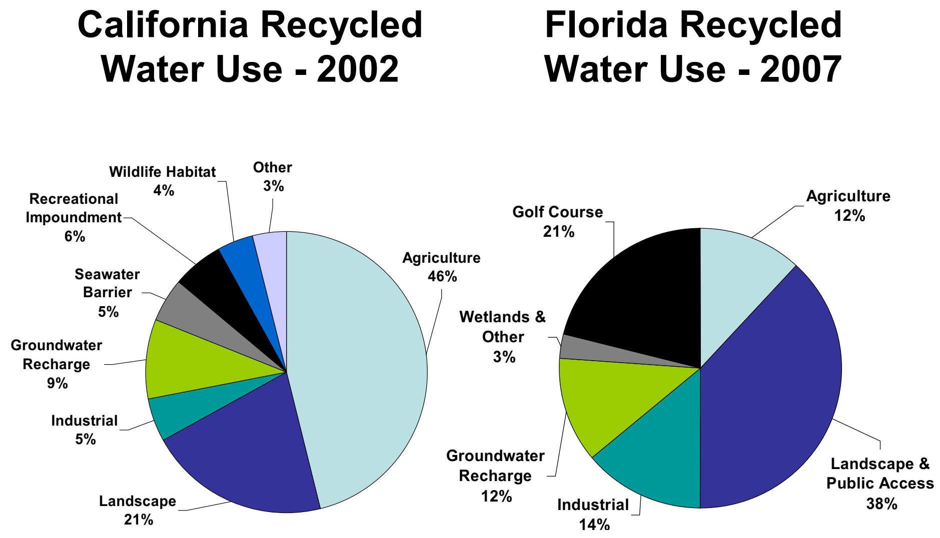

Figure 2. Water reuse in California and Florida.

The Advantages of Closely Spaced Emitters

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Abstract. *There are many advantages in using drip irrigation with closely spaced emitters. In fruit and vegetable row crop production, many producers are successfully using drip tape systems to germinate seed and set transplants without the traditional use of sprinklers. A technique common to their success is the use of drip tape with closely spaced emitters to achieve desired wetting patterns, and the specific techniques of three producers growing strawberries and celery in California and onions in Oregon are studied. Benefits include reduced runoff and decreased water, labor, equipment and energy costs associated with sprinkler irrigation. Additional benefits include reduced weed germination, improved field accessibility, reduced incidence of disease, improved planting bed tilth, improved food safety and improved farm safety. In addition, a field trial conducted by Clearwater Supply in Ontario, OR showed that drip tape with emitters spaced 8 inches apart created superior wetting patterns than drip tape with emitters spaced 12 inches apart. Finally, a review of a recent report from Cal Poly San Luis Obispo's Irrigation and Training Research Center (ITRC) reveals that closely spaced emitters can improve salinity management, can provide a better wetted pattern, can increase crop quality, and can reduced both purchase and operational costs versus wider spaced emitters.*

Keywords. Irrigation, drip, drip irrigation, subsurface drip irrigation, SDI, drip tape, tape spacing, emitter spacing, wetting pattern, sprinkler irrigation, runoff, labor, energy, seed germination, transplant setting, strawberry, celery, lettuce, onion, artichoke, organic, weed germination, disease, farm safety, food safety, salinity.

Introduction

Many fruit and vegetable row crop growers use drip tape with closely spaced emitters as their primary irrigation method in their growing system, but also use a secondary sprinkler system to germinate the seed or "set" the transplants at the beginning of the season. This secondary sprinkler system often wastes water where conditions are hilly or windy, and where plastic mulch is present, because irrigation water runs off and is not beneficially used. In some cases, this runoff water contaminates other water resources or erodes soil. Further, the use of a secondary sprinkler system requires additional expense for the sprinkler equipment itself, for the labor to move the pipe, and for the energy to achieve higher pumping pressures. For these reasons, innovative growers have developed ways to use the existing drip irrigation system to supply adequate germination and transplant moisture, and have found that the use of closely spaced emitters contributes to their success. The obvious benefits are reduced costs and improved usage of existing resources, but other benefits have been reported as well.

Growers cite significant cultural advantages to eliminating sprinkler use. First, weed germination is reduced since drip targets irrigation water to the planting bed while sprinklers wet the entire field, including furrows, field edges and roads. Thus, unwanted weeds are germinated with sprinklers that require cultivation, hand weeding and/or herbicide treatment. This is especially important in organic fields where expensive hand labor must be used to weed since herbicide use is prohibited. Second, the incidence of disease is reduced since the plant canopy remains dry and the air less humid. This has significantly reduced fungicide sprays and/or crop loss, and again is especially important in organic fields where fungicide use is prohibited. Third, field accessibility is improved since sprinkler pipe does not impede other cultural operations. Fourth, the planting bed remains soft and is not hardened or crusted over from the use of sprinklers. Fifth, food safety may be enhanced since less standing water is available to harbor E.Coli. And sixth, farm safety conditions may be improved since heavy sprinkler pipe is no longer moved by laborers through uneven terrain that is often steep and/or muddy.

The following discussion examines actual case studies of three growers who have successfully germinated seed and set transplants with closely spaced emitters. Their techniques are presented, along with the varied benefits. In addition, field studies conducted by Clearwater Supply in Ontario, Oregon are reviewed which compare the wetting patterns of two different emitter spacings, 8 inch versus 12 inch. Finally, excerpts from Cal Poly San Luis Obispo's "Drip and Micro Irrigation Design and Management" manual published in 2007 by the Irrigation Training and Research Center (ITRC) are provided in support of the use of closely spaced emitters to improve salinity management, to create better wetting patterns, to increase crop quality, and to reduce both purchase and operational costs versus wider spaced emitters.

Case Study 1: Reiter Berry Farms, Watsonville, CA

Frank Estrada, area manager for Reiter Berry Farms in Watsonville, California manages over 300 acres of strawberries for Driscoll and sets strawberry transplants with drip irrigation. "We stopped using sprinklers over three years ago for anything except pre-irrigation prior to bed prep," says Reiter. He reports that soil prep, tape placement and irrigation scheduling are the keys to success, and that beds must be square and consistent with 27-29 inch wide tops. For strawberries on 52 inch centers, two rows of premium drip tape with closely spaced outlets and a high flow rate are placed in the center of a dry bed, 10 inches apart, and buried 0.5 – 1.0 inch deep. The beds are then irrigated about 3-4 hours and marked. Then, transplants are placed 5 inches from each tape line on the bed shoulder and packed in by laborers, and then machine rolled. The block is then immediately irrigated until water from the drip lines begins to bleed from the beds. In a clay loam, this occurs after about 8 hours of irrigation. In a sandy loam, this occurs sooner, and may require more frequent irrigation for shorter duration.

"There is no difference in quality or production in my 'drip only' fields versus sprinkler fields," says Estrada. "We save in sprinkler equipment and labor costs, and use less water and energy

Total bed width is 27-29 inches wide.

Tape is placed 10 inches apart, about 0.5 – 1.0 inches deep.

Strawberry transplants will be placed 5 inches from each of the tape lines.

during the first two weeks of production. Since drip runs at lower pressures and wastes less water than sprinklers, using drip for the rest of the season saves water and energy over sprinklers as well." Another reason Estrada prefers drip to sprinklers is the reduced incidence of weeds in his organic fields. "With drip, I'm not applying water in-between the beds, so weed growth is greatly reduced. With sprinklers, weeds germinate everywhere and I am forced to hand weed, which is expensive."

Case Study 2: Naumann Ranch, Oxnard, CA

Mike Naumann of Naumann Ranch in Oxnard, California manages 800 acres of mixed vegetables along with his brother Brian. "We haven't used flood or sprinklers for years," says Naumann. This was accomplished by developing a simple valve and layflat system that allows immediate irrigation of new celery transplants. "After each pass of the transplant machine, we open up additional drip lines with closely spaced emitters from the layflat by changing positions of an improvised marine valve – this way, newly transplanted rows receive water *immediately* after planting," says Naumann. "This is in contrast to waiting for an entire block to be completed. The result is reduced mortality and stronger plant growth. Not only have we increased yields and uniformity, but we have eliminated the expense of bringing in traditional sprinklers to set transplants, and the unwanted side effect of runoff."

A valve opens up additional drip lines after each pass of the transplant machine.

Rollers help to properly secure the transplants in the soil such that the entire bed is quickly 'blackened' with moisture soon after the drip lines are pressurized. "If we were using sprinklers, the plants would have to wait until the block is completely planted, and would likely stress before receiving water. The logistics of above ground pipelines would be difficult to work around as well, and windy conditions often ruin sprinkler uniformity and drift water into unwanted fields or roadways. We have cut water use in half compared to other irrigation methods used in the past, and have also saved on irrigation labor which reduces our costs." In the same geographic region, artichoke transplants are set with drip tape as well.

Rollers help secure the transplants in the bed.

Food safety is one of the more difficult challenges vegetable growers face. "Given the current pressures regarding food safety, we don't feel we could even farm if it weren't for drip," continues Naumann. The Naumanns believe their drip irrigation and harvest practices help safeguard them from the potential disasters that other growers have experienced in recent months and years. "E. Coli grows where there is water. In drip irrigated fields, less area is irrigated, and it is likely that less water runs off or is left standing," says Michael Cahn, University of California Farm Adviser in Monterey County, CA. Thus, avoiding sprinkler usage may contribute to food safety as well.

Celery is transplanted into dry soil.

Drip tape with closely spaced emitters quickly blackens the bed with moisture immediately after transplanting.

Case Study 3: Standage Farms, Inc., Vale, OR

Larry Standage of Standage Farms, Inc. in Vale, Oregon germinates onion seeds with his drip irrigation system. The drip tape is installed after the onion seeds are planted, the tape supplying the moisture for germination. Drip tape outlets are spaced 12 inches apart, and the tape flow rate of .22 gpm/100’ translates into an application rate of .06 inches per hour. Standage feels that the best wetting pattern is achieved with a 12 hour set, with intervals between irrigations determined by weather and sensors.

“Drip nurtures a healthier, stronger plant, which really shows up during extreme heat events,” explains Standage. “Drip also creates an advantage for cultural activities

Germinating onion seed with closely spaced emitters helps ensure uniform production in size, shape and color.

during the growing season since the furrows are always dry as opposed to flood, which always leaves wet spots. The root system is more robust which prevents stress, and uniformity of water application translates into uniformity of crop. This is a huge advantage for our customers, and even in our own packing sheds, because variable size, shape and color creates problems in both packing and marketing. The contents of each 50 pound bag of onions is superior because the crop is more uniform in size, shape and color, thus the customer is more pleased. I use drip to keep my customers coming back."

Other growers are successfully germinating lettuce seed using similar bed shaping, tape placement and irrigation scheduling techniques. After germination, the lettuce seedlings are thinned to a final spacing by hand with a hoe. The benefits include keeping the furrows dry to avoid weed germination, and reducing disease pressures. These two benefits are especially important in organic production where treatment is very expensive without chemicals. Improved bed softness is also cited as a benefit of drip versus sprinklers.

Lettuce seeds are germinated with closely spaced emitters.

Seedlings are then thinned with a hoe.

Field Trial by Clearwater Supply

A field trial conducted by Jim Klauzer of Clearwater Supply in Othello, Oregon provides visual evidence of the advantages of closely spaced emitters to achieve desirable wetting patterns. The top photo below shows a 12 inch emitter spacing on the left, and an 8 inch spacing on the right. Both tapes emit the same amount of water: .22 gpm/100'. The soil is an Elijah – Sebree silt loam, one of the more difficult soils in the Treasure Valley. Clearly, the 8 inch spacing is creating a wetting corridor more quickly than the 12 inch spacing, a big plus for growers who seek to germinate seed and set transplants with drip. The photo on the bottom shows the 8 inch spacing after 30 hours of irrigation, where nearly the entire planting bed has been moistened. This type of wetting pattern is essential to germinate seed or set transplants without the use of sprinklers.

Above: Toro Aqua-Traxx drip tape, 12 inch spacing, .22 gpm/100’ on left; 8 inch spacing, .22 gpm/100’ on right.

Below: Toro Aqua-Traxx drip tape, 8 inch spacing, 0.22 gpm/100’ after 30 hours of irrigation.

ITRC Excerpts Regarding Emitter Spacing

Choosing the right drip tape emitter spacing can be more of an art than a science. This is because of the many variables that exist in each farming application, including tape placement, soil type, crop, plant population, soil and water salinity, tape quality and cost, etc. Fortunately, Cal Poly San Luis Obispo's recent Drip and Micro Irrigation Design and Management Manual, published by the Irrigation Training and Research Center (ITRC) in 2007, provides a great deal of guidance for this important decision. In particular, the new manual discusses how closely spaced drip tape emitters can enhance salt management for seed germination, leach salts in permanent crops, and dilute soil salinity for salt sensitive crops. In addition, the manual highlights some of the agronomic and economic disadvantages of using widely spaced emitters. The following provides some discussion and excerpts from the manual.

Closer Emitters Improve Salinity Management

Salinity management is especially important during seed germination and emergence, and closely spaced emitters and bed shape can help. "Use surface tape (or tape only a few centimeters below the soil's surface) with closely spaced emitters to leach salts downward. In more arid areas, widely spaced holes (i.e. one tape for every two rows, or hole spacing greater than 16") can cause salt buildup between the holes. If seeds are later planted in those salty areas, they will not emerge. Decades of experience with flood irrigation has taught farmers to shape furrows so that salt-laden irrigation water evaporates at high points in the bed – and the plants/seeds are located at lower points. Likewise, drip irrigated beds should be shaped with an indentation where salts will accumulate away from the seed line planted below the indentation." (pgs.76-77).

Salinity management is also important in established drip irrigated orchards and vineyards. Drip laterals typically wet less than 40% of the total soil surface, and over time, salts carried to this wetted strip through the irrigation water will safely leach away from the soil close to the emitter. However, salts will concentrate in the soil as distance from the emitter increases. For this reason, the standard "leaching requirement" equations and principles for maintenance leaching are not applicable for drip/micro irrigation. Instead, periodic "reclamation" leaching is needed to remove the salt from these outer zones of the soil.

For reclamation, broadcast flood or sprinkler irrigation is typically used to leach these concentrated salts below the root zone, but this can be wasteful since only 20-40% of the surface area of the orchard or vineyard needs to be leached. "If 100% of the soil area is wet to treat this 20-40% of the area, 2.5 to 5.0 times the necessary leaching water will be

Low-flow drip tapes, spaced 0.30 m apart, used to apply the leaching water. From ITRC page 82.

applied. Most of the water is ineffective because it is applied to zones that do not need leaching." Instead, ITRC researchers have suggested using a portable drip tape system to "target leach" the orchard or vineyard dripline zone. In 2005, Burt and Isbell showed that salts were effectively removed in a pistachio orchard using six lines of retrievable surface drip tape with emitters spaced closely, 12 inches apart, to "target leach" the dripline zone. Subsequent leaching experiments closely match the pistachio orchard results. Once leaching is complete, the drip tape can be retrieved and reused. In this way, closely spaced tape emitters perform leaching with less water (pgs. 82-83).

Drip irrigation can also help dilute soil salinity such that yields may be improved. Yields typically decrease once the soil salinity reaches a threshold value, and as the soil dries in-between traditional irrigations, salinity concentration becomes worse. Irrigating frequently with closely spaced emitters can help. "Years of experience with drip have shown that if it is managed so that the soil salinity remains dilute, yields can be higher than they would be with the same water quality using sprinklers or furrow irrigation. For some crops such as processing tomatoes, some research has observed (Hanson and May, 2003) that on very salty fields the crops have no damage even though the salinity levels would traditionally cause serious yield declines." (pg. 86).

Closer Emitters Provide a Better Wetting Pattern for Better Results

Closely spaced emitters can also help achieve the right wetting pattern, increase crop quality and reduce both purchase and operational costs vs. wider spaced emitters. "For the Central Coast of California, most growers use an emitter spacing of 8 inches – 16 inches, with a shallow burial depth. Even with these close spacings it may be important to match the spacing to the soil type. Closer hole spacings can result in a more continuous soil wetting pattern. The most common hole spacing in California is 12 inches. Eighteen inch spacing is often too great. In order to use wide spacing (in SDI applications), one must do all of the following: a) Raise the pressure to 20 psi during germination to provide a higher flow rate that subs better, b) Apply water to the soil surface until it is very wet (in fact, water will actually be standing in the furrows), and c) Use heavy wall drip tape (about 15 mil) in order to handle the high pressure without tape damage." (pg. 288.)

Clearly, buying heavier mil tape, increasing pressures and wetting the soil surface are all undesirable side effects of using widely spaced emitters in an SDI application. Initial buying costs and post-purchase operation costs will be higher, and soil surface wetting may damage crop quality and/or encourage unwanted weed growth. For optimal performance, closely spaced emitters are often the best choice.

In summary, ITRC's new manual points out that properly managed drip systems with closely spaced emitters have many advantages. First, closely spaced emitters can help push salts away from seeds and enhance germination. Second, closely spaced emitters can be used to perform reclamation leaching in orchards and vineyards and significantly reduce water requirements for this task. Third, closely spaced emitters help to dilute soil salinity such that crop yield is not adversely affected. And fourth, closely spaced emitters can be used to manipulate the wetting pattern as desired without raising pressures or requiring thicker mil tapes.

Drip tape with closely spaced emitters is used to set celery transplants along California's Central Coast.

Conclusion

In conclusion, the fruit and vegetable row crop producers profiled are successfully germinating seed and setting transplants with closely spaced emitters instead of using sprinkler systems for this specific task. The use of closely spaced emitters helps to achieve the desired wetting pattern, which is essential to germination and transplant setting success. In addition, growers pay special attention to soil preparation, drip tape placement and irrigation scheduling. In addition, they have developed special techniques to immediately apply moisture to rows of transplants immediately after the transplant machine completes each pass.

The obvious benefits of using closely spaced emitters to eliminate the use of sprinklers for germination and transplants are numerous. First, the costs associated with the use of sprinklers is obviously reduced. Second, runoff and water use is reduced, and existing resource use is improved. Third, weed germination is reduced since drip targets irrigation water to the planting bed while sprinklers wet the entire field, including furrows, field edges and roads. Fourth, the incidence of disease is reduced since the plant canopy remains dry and the air less humid. Fifth, field accessibility is improved since sprinkler pipe does not impede other cultural operations. Sixth, the planting bed remains soft and is not hardened or crusted over from the use of sprinklers. Seventh, food safety may be enhanced since less standing water is available to harbor E.Coli. And eighth, farm safety conditions may be improved since heavy sprinkler pipe is no longer moved by laborers through uneven terrain that is often steep and/or muddy.

In a field trial conducted by a dealer in Oregon, the use of drip tape with emitters spaced 8 inches apart created superior wetting patterns versus drip tape with emitters spaced 12 inches apart. Finally, a review of a recent report from Cal Poly San Luis Obispo's Irrigation and Training Research Center (ITRC) reveals that closely spaced emitters can improve salinity management, can provide a better wetted pattern, can increase crop quality, and can reduced both purchase and operational costs versus wider spaced emitters.

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TENSIOMETER CONTROLLED AUTOMATED IRRIGATION SYSTEM FOR CHRISTMAS TREE PRODUCTION

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Abstract.

Irrigation of short rotation trees such as *Abies fraseri* for Christmas tree production is gaining importance in the upper Midwest due to the intensive planting of this species out of its natural range. However, current irrigation scheduling practices rely on empirical observations with very limited automation used. The paper discusses the design, setup, and maintenance of a tensiometer based automated system for *Abies fraseri* trees in a Christmas tree production system. Soil tensiometers equipped with 4-20mA transducers were installed in various plots on drip irrigated *A. fraseri* Christmas tree farms. The transducers were wired to a CR1000 datalogger through an AM16/32 Multiplexer. Water on-demand was controlled by soil moisture tension levels that triggered the stimulation of a CD16AC unit wired to solenoids delivering irrigation water to the various treatments. The datalogger was connected to a remote computer with a static IP address through a raven modem using a wireless cellphone connection. The system functioned according to the design as expected. However, several issues associated with tensiometers, computer programming, and system wiring created some challenges regarding the reliability and transferability of such system to commercial facilities.

Keywords. *Tensiometers, CR1000 datalogger, automated irrigation, Christmas trees, Soil matric potential*

INTRODUCTION

Christmas trees are short rotation perennial crops grown from seed in a nursery for 2 to 5 years, then moved into a plantation where they are raised for an additional 6 to 9 years until the mature harvestable size of approximately 2.1 m (Nzokou et al., 2007). During the last decade, Fraser fir (*Abies fraseri*) has become the most economically important species grown for Christmas tree purposes (Koelling et al., 1992; Nzokou and Leefers, 2007). The species represents about 40% of the estimated 3.5 million trees sold in Michigan, and is also the main species in most producing states in the Midwest and eastern United States (Nzokou et al., 2007). In the upper Midwest, supplemental water must be applied to meet the physiological needs of this species (Koelling et al., 1992; Nzokou and Leefers, 2007). However, in current production practices, irrigation decisions are based on personal observations or empirical knowledge, with a rule of thumb guideline of 2.5 cm of water applied weekly in the absence of rainfall. This practice lags far behind modern irrigation practices in agriculture that use crop assessment, fixed time allocation, or soil moisture variation for scheduling irrigation.

Plant assessment methods include empirical crop water stress index (CWSI) used on a variety of crops including corn (Irmak et al., 2000; Yazar et al., 1999), sunflower (Erdem et al., 2006), watermelon (Orta et al., 2003), and grass and forage crops (Al-Faraj et al., 2001; Payero et al., 2005). Daily changes in diameter (Fereres and Goldhamer, 2003), and visual indices (Jones, 2004) have also been used.

An alternative to crop assessment is to base irrigation scheduling on changes in soil moisture. Irrigating based on changes in soil moisture conditions is relatively simple and easy to apply in practice (Jones, 2004). Soil based assessments are built on constant monitoring of changes in soil moisture content using the hand feel method (Bolen, 1984; VanderGulik, 1997), or a soil moisture measuring device (tensiometers, TDR). This paper reports on the design, set up, and maintenance of an automated irrigation system based on soil moisture variation monitored with tensiometers.

Tensiometer based systems have been used for high input agriculture, in which fertilizers and pesticides are applied. Oki et al. (1996) found that using an automated irrigation system controlled by three different soil tension thresholds resulted in more efficient water use, reductions in pollution run-off, and increase in growth compared to a manually-controlled system. Munoz-Carpena et al. (2005) found that maintaining soil tension levels of 15 kPa resulted in a 73% reduction in water use and no adverse effect on quality compared to a manually irrigated system. Another report indicated that the total marketable yield decreased linearly from tension levels of 10 kPa to 20 kPa (Smajstrla and Locascio, 1996). These studies indicate potential benefits for tensiometer based automated systems for irrigation scheduling.

Automated systems can potentially decrease the overall cost of operating irrigation systems due to reductions in water use (Clark et al., 2007). An automated water on-demand system would be particularly useful for the production of short rotation intensively managed systems such as Fraser fir Christmas tree production. In Fraser fir Christmas tree production, large acreages are often irrigated, taking several days or more to complete. Reducing the labor required for managing these large scale systems could prove substantial and improve the overall profitability of the operation.

Despite the benefits, tensiometers are also known to be difficult to maintain due to their poor adaptability to dry conditions, vacuum breakage, and variability in measurements (Nzokou et al., 2007). Therefore, challenges associated with the inclusion of these devices into an automated irrigation system need to be identified and addressed.

The goal of this project is to design, construct, and implement a tensiometer based automated irrigation system for Fraser fir Christmas tree plantations that would: 1) use existing technologies, 2) apply water based on changes in soil moisture content, 3) provide operational flexibility, 4) interface with a computer for system changes, data collection, and system modifications. This paper describes the hardware and software components of the system and presents preliminary plant growth data achieved under this automated method.

MATERIAL AND METHODS

Location and Design

The automated irrigation systems were constructed for experimental purposes at two Christmas tree farms in Michigan. The farms are located in Horton, Michigan and Sidney, Michigan. At the Horton farm, the existing drip irrigation system was excavated and modified to divide the field into smaller zones allowing independent control of irrigation for each zone. At the Sidney location, a new drip irrigation system was designed and constructed for the purpose of this study (Figure 1).

There are 5 components to the system: 1) a standard drip irrigation system with a 3.75 cm (1.5 inch) main line and a 2.5 cm (1 inch) sub-main line supplying drip lines with low pressure water flow, 2) solenoid valves controlling the water flow to each irrigation zone, 3) soil moisture tensiometers placed in each irrigation zone, 4) a control system including datalogging equipment and a controller able to activate the solenoids. The system is based on a simple feedback loop with the soil moisture tension (tensiometer reading) used as control parameter, and a water cycle starting when the soil moisture tension reaches a predetermined threshold. At each location, the field was divided into smaller (approximately 0.2 acres) irrigation zones for various irrigation treatments as indicated in figure 1.

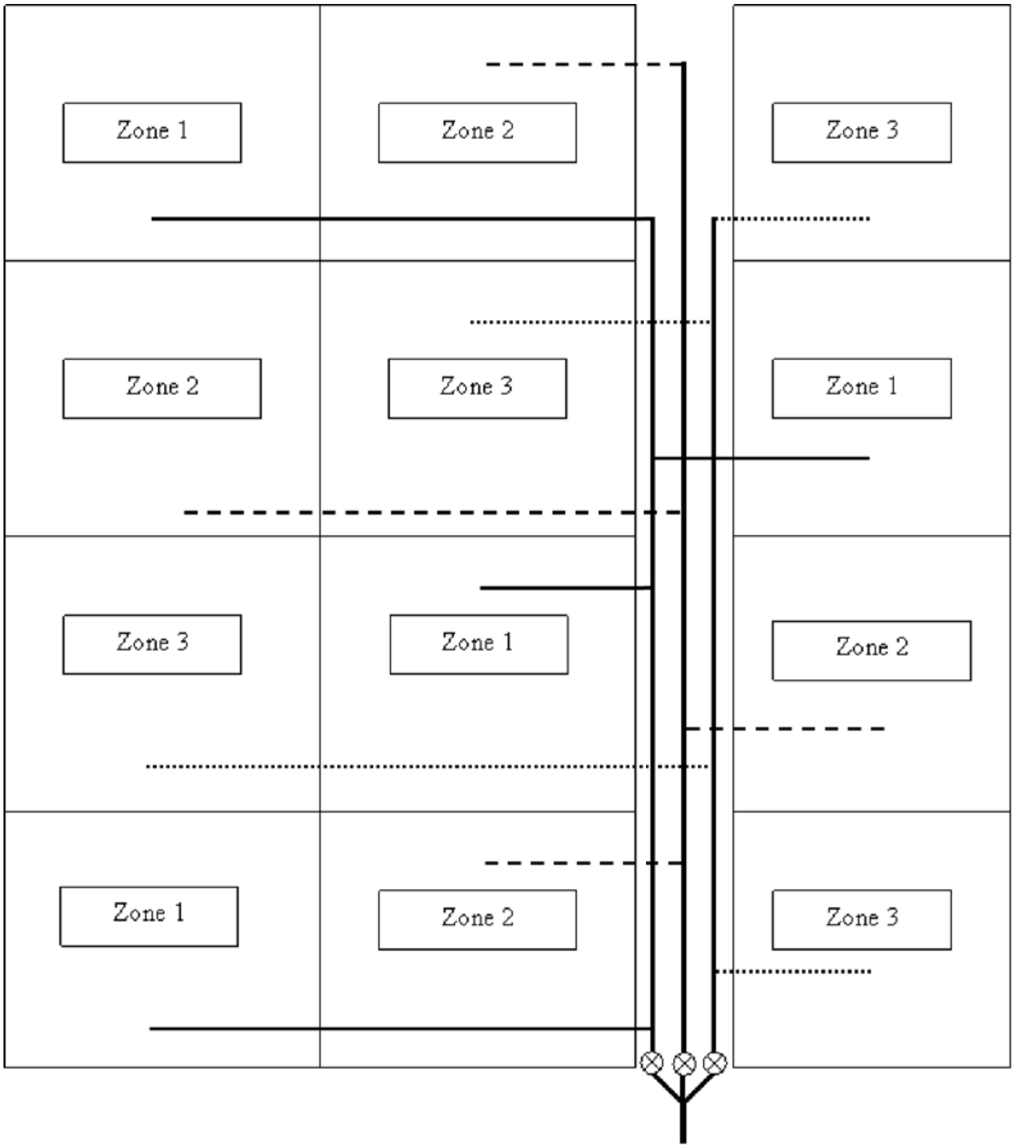

Figure 1: Field divided into irrigation zones controlled by solenoids. Each zone corresponds to an irrigation treatment.

For each system, a CR1000 datalogger was installed in an enclosure on a CM10 tripod (Campbell scientific Co.). Weather sensors including a 03101 R.M Young Sentry anemometer, a TE525 tipping bucket rain gage, a HMP50 temperature and relative humidity probe, and a CS300 pyranometer (Campbell Scientific Co.) were installed on the tripod and wired to the datalogger for continuous measurement (Figure 2).

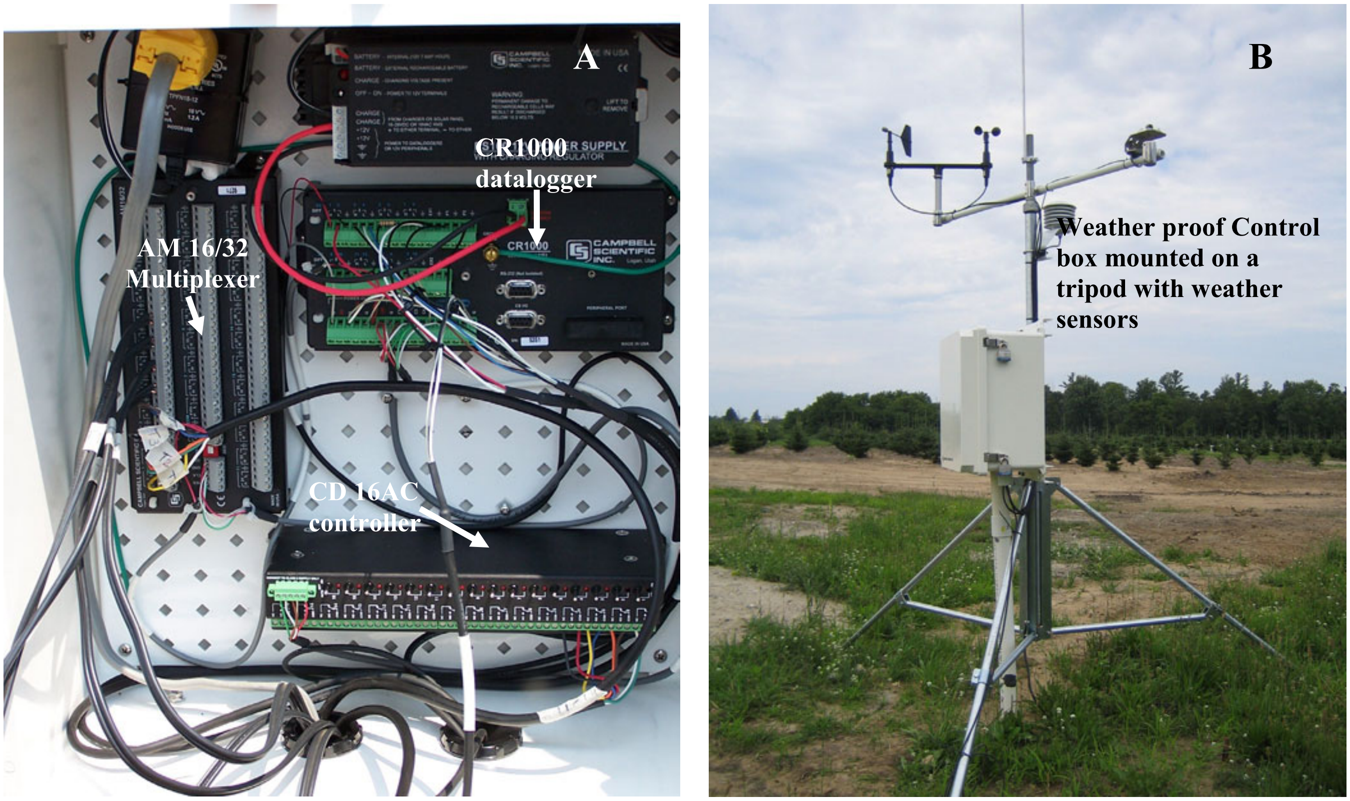

Figure 2. CR1000 datalogger, multiplexer and control in enclosure (A), and overall system mounted on tripod with weather sensors (B).

Tensiometers

A tensiometer is a device made of a sealed plastic (or glass) tube with a porous ceramic tip on one end, a screwable cover and a vacuum gauge on the other end (Figure 2). The vacuum gauge is calibrated in centibars (or cb) and graduated from 0 to 93cb (this can vary with the brand or tensiometer type). Tensiometers are sold as 12” (30 cm), 18” (45 cm), and 24” (60 cm). The tube is air tight and water filled and under vacuum when in operation. When installed in the ground, water moves freely from the ceramic tips into the surrounding soil environment as the ground dries, or from the soil into the tubes as the moisture content into the surrounding soil increases. Tensiometers measure the soil water matric potential, defined by the Soil Science Society of America (Young and Sisson, 2002) as “the amount of work that must be done per specific quantity of pure water from a specified source to a specified destination”. As soil dries with warm weather and no or little rainfall, water is drawn out of the instrument, reducing the water volume in the tube and creating a partial vacuum that is registered on the gauge. Consequently, the drier the soil, the greater the force per unit area holding the remaining water in the soil, and the higher the reading. Conversely, when it rains and soil receives water, the vacuum created inside the tube will suck water back into the tube and lower the gauge reading.

For this project we used 30 and 60 cm tensiometers (Irrometer Company Riverside, CA) placed in each zone. The 30 cm tensiometer was used to make irrigation decisions and the 60 cm tensiometer helped understand the soil moisture gradient from the surface to deeper soil profiles. Tensiometers were placed along the drip line and spaced away from each drip emitter so that the distance from the tree to the emitter was approximately the distance from the tensiometer to the nearest emitter (Hung, 1995).

Each tensiometer was equipped with a 4-20 milliamp (ma) remote sensing units (RSU) for connection to a CR1000 data logger (CR1000 Campbell Scientific Logan, Utah). The RSU units were all calibrated by the Irrometer Company and ready to use when received. Due to the large number of tensiometers connected to the system, an AM16/32 multiplexer was used to increase the number of connection possibilities. The data logger read 12-24 millivolts (mv) when it scanned each terminal. Consequently, it was necessary to add 100 ohm resistors (CURS100) to each terminal to convert the 4-20 ma signal into a voltage signal that the datalogger could recognize during each scan. All tensiometers were hard wired to the datalogger using this approach.

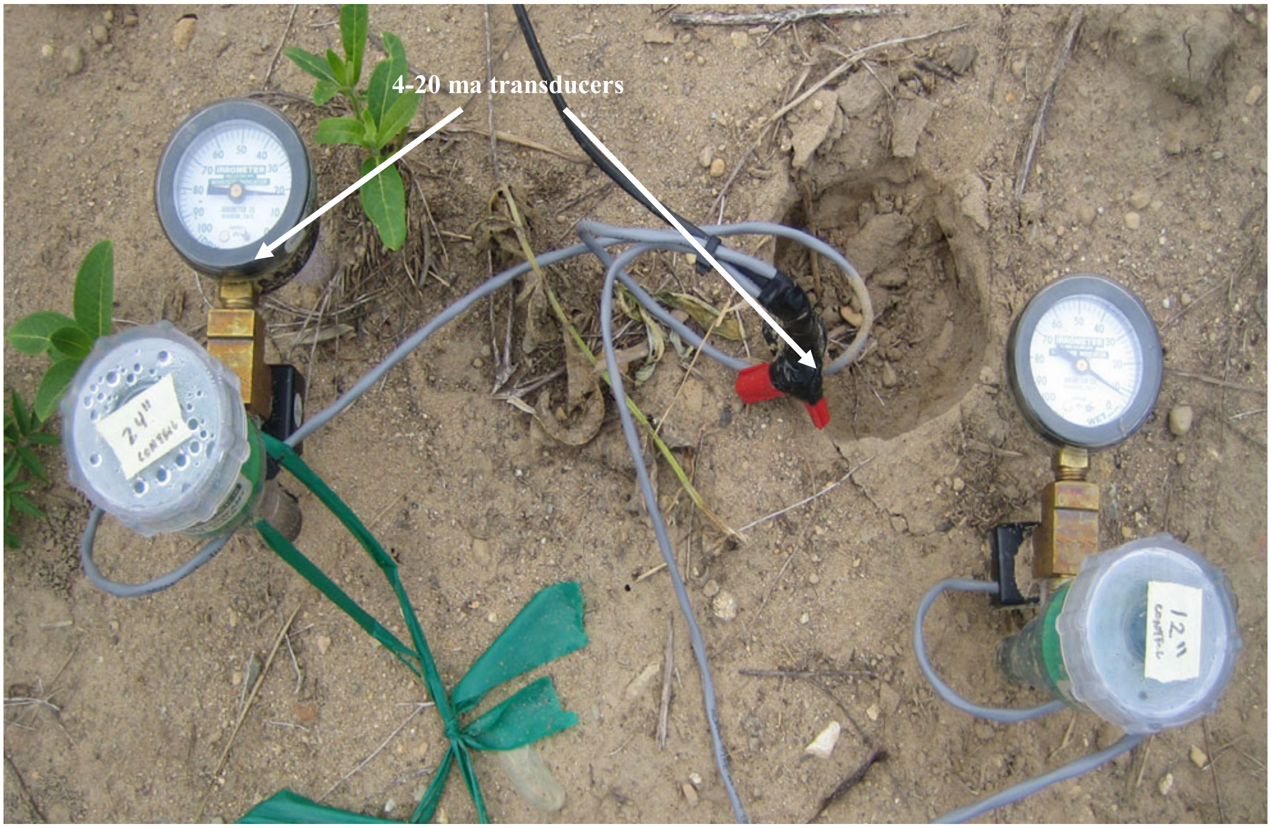

Figure 3: Tensiometers (30 cm and 60 cm) installed in the ground. Each tensiometer had a vacuum gauge and 4-20 ma transducer wired to the multiplexer.

In addition, a SDM-CD16AC AC/DC channel controller (Campbell Scientific Co.) was added in order to automate the system. The channel controller was wired to the datalogger and connected to the solenoids (5V, 24V relays) controlling each irrigation zone or treatment. The overall wiring diagram connecting all the pieces and devices of the system is presented in Appendix 1.

Irrigation decisions

Water application was controlled by soil moisture tension levels specified for each treatment with goal of investigating the effect of low to high soil matric potential (tensiometer readings) on the height and diameter growth of trees at various stages of the rotation.

Table 1: Irrigation thresholds (on/off tolerances) to maintain various tension levels in zones controlled by a tensiometer based automated irrigation system.

Zone	Tensiometer depth	Stop irrigation	Target tension	Start irrigation
1	30 cm		Non-irrigated	
	60 cm			
2	30 cm	≤ 13 kPa	15 kPa	≥ 17 kPa
	60 cm			
3	30 cm	≤ 23 kPa	25 kPa	≥ 27 kPa
	60 cm			
4	30 cm	≤ 33 kPa	35 kPa	≥ 37 kPa
	60 cm			
5	30 cm	≤ 43 kPa	45 kPa	≥ 47 kPa
	60 cm			

The margin was set at ±2 kPa tension range for each of the different zones, with the exception of the non-irrigated zone. If the tension exceeded this range, the system would activate a valve that would initiate an irrigation event in the corresponding zone. Irrigation would stop when the tension reached the low range of the ±2 kPa threshold, based on the target tension. For example, for the 15 kPa irrigation threshold, the system would start if soil moisture tension reached 17 kPa, and would stop as soon as it was below 13 kPa. As indicated, irrigation decisions were based on the reading of the 30 cm tensiometer. Even so, trigger levels could be adjusted to take into account soil physical characteristics, the tree water needs of the tree and its growth stage. The computer program for the specific instruction described above will be as follows:

Monitoring and wireless communication

The CR1000 data logger offers different options for collecting data. Using either PC400 or LoggerNet data logger support software (Campbell Scientific), direct connection is possible using the RS-232 port, linking a portable computer and the datalogger with a serial cable. However, a direct cable connection requires a computer and an operator at the location of the data logger for data download (Cheek and Wilkes, 1994; Shukla et al., 2006). Therefore, the option of using wireless communication was very attractive for constant remote monitoring of the data logger and the overall functioning of the system. For this purpose, a Raven100 CDMA Airlink Cellular Modem (Campbell Scientific Inc.) was purchased and wired to the RS-232 port on the datalogger. The Raven100 CDMA modem has a PN 18285 1dBd Owni Directional antenna mounted on the system tripod. A data account using a dedicated IP address for each system was setup with Alltel for remote connection to each station from our office.

This setup allows greater flexibility with regular monitoring of the system, and data collection. In addition, customization of the software and data collection allowed for incorporation of charts and graphs for a visual representation of data and alarm notifications in the event of a malfunction.

The system was operated by a computer program created using “shortcut” in the PC400 software (Campbell Scientific). The program developed using visual basic coding language, defines units, and provides specific instructions with all coefficients and transformations necessary to collect data that are directly usable. Furthermore, several table definitions summarizing data based on a predefined schedule were created and inserted into the program. The first page example of the program is presented in Appendix 1.

Budgeting and cost considerations

Compared to a manually controlled irrigation system, an automated system is more expensive initially due to purchasing the equipment. However, these costs averaged over the life of the irrigation system are likely to be considerably cheaper than the manually controlled alternative. Table 3 shows a summary of costs of the various components and labor required to implement a system of this nature. Based on our experience, the cost for building an automated irrigation system on 1 ha is $7,692. The cost of a drip irrigation system, exclusive of automation, can range from $1,500 to $3,500/ha with maintenance costs ranging from $50 to $200/ha/yr (Ayars et al., 2007). The $2,500 irrigation system cost is based on the assumption that 80% of the cost is for drip tube, 15% for main and sub-mainlines, and 5% for connections and valves. Depending on the quantity, quality, and complexity of the desired components, costs could vary greatly. The cost for adding the automation as part of the irrigation system ($4,942) is based on the assumption that one 30 cm and 60 cm tensiometer represent a single zone; therefore, increasing the number of zones will add to costs. Labor associated with the automated system ($1000) relates to the time required to setup and properly implement the system in situ. Due to the complexity of connecting and programming an automated irrigation system, there may be the possibility of a lengthy learning curve or need for technical assistance, which could increase costs. Since the tensiometers require connection to the data logger and peripherals, increasing the tensiometers beyond the means of the data logger might require the purchase of additional peripherals, further increasing costs. The wireless service necessary to access, modify, and view the workings of the irrigation system is based on a standard limited access data account and can vary among wireless carriers and usage. The cost summary listed in Table 2 is presented as a starting point to the investment required in building an automated system.

Table 2: Total costs for components and materials associated with building an automated irrigation data based on actual expenses with a local irrigation supplier.

	Automation / Measuring System		Irrigation System	
Item	**Description**	**Costs ($)**	**Description**	**Costs ($)**
Components	CR1000 Data logger	1,350	Trickle tube[2]	2000
	SDM-CD16AC Controller	695	Pipes: main, sub-main[2]	375
	AM16/32 Multiplexer	560	Connections / valves[2]	125
	Tensiometer (30 cm)	165		
	Tensiometer (61 cm)	185		
	CURS100 Resistor	52		
	Wireless Modem	340		
	LoggerNet Software	545		
	Wireless service[1]	50	Installation	100
Labor	Set up	1,000	Maintenance[3]	150
Subtotals		**4,942**		**2,750**
Total cost				**7,692**

[1]cost/mo [2]cost/ha [3]cost/yr

DATA EXAMPLE

Tensiometer readings

A summary example of tensiometer readings for the 15 KPa and 25 KPa treatments from July 8, 2006 (Day of the year 189) and October 25, 2006 (Day of the year 275) is presented in Figure 4). During the period from DOY 189 to DOY 230, there was no rainfall in the area. The figure indicates that readings for both tensiometers increased as the site conditions become drier, until the water cycle started at day 202 for the 15 KPa. The 25 KPa tensiometer continued to rise until day 210, dropping following a watering event that started once the reading for reached 27 KPa (irrigation threshold for the 25 KPa tensiometer). Similar cycles were repeated between day 223 and day 230. Following these two irrigation cycles, soil moisture remained below irrigation thresholds for both tensiometers until the end of the measurement period on October 25.

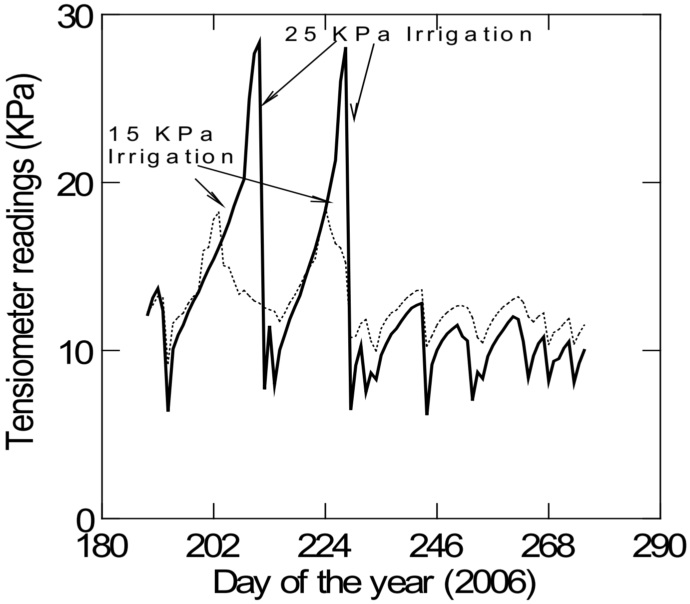

Figure 4. Tensiometers (15 KPa and 25 KPa) readings for the period between July 8 and October 25, 2006. Readings above the threshold for each level was followed by a quick drop caused by an irrigation event.

Influence of irrigation treatment on growth

The effect of the various irrigation treatments on growth response is summarized in Figure 5. The height growth for each tree measured was normalized by dividing by initial growth to account for size differences in trees before treatments were applied. The overall trend of the data shows a positive response to irrigation treatments for trees in smaller height classes (0.6m< to 1.2-1.5m) in 2006 (Fig. 5-A) and 2007 (Fig. 5-B). The relative growth of trees receiving irrigation at the 15 and 25 KPa thresholds was significantly higher ($P<0.05$) than non-irrigated trees for height classes 0.6 m and below (2006 and 2007) and 0.6-0.9m (2006). Growth response was generally positive for medium size trees (0.9-1.5m) for both years, but results were more variable and not always statistically significant. Height growth of tall trees (1.5m and above) did not respond to irrigation.

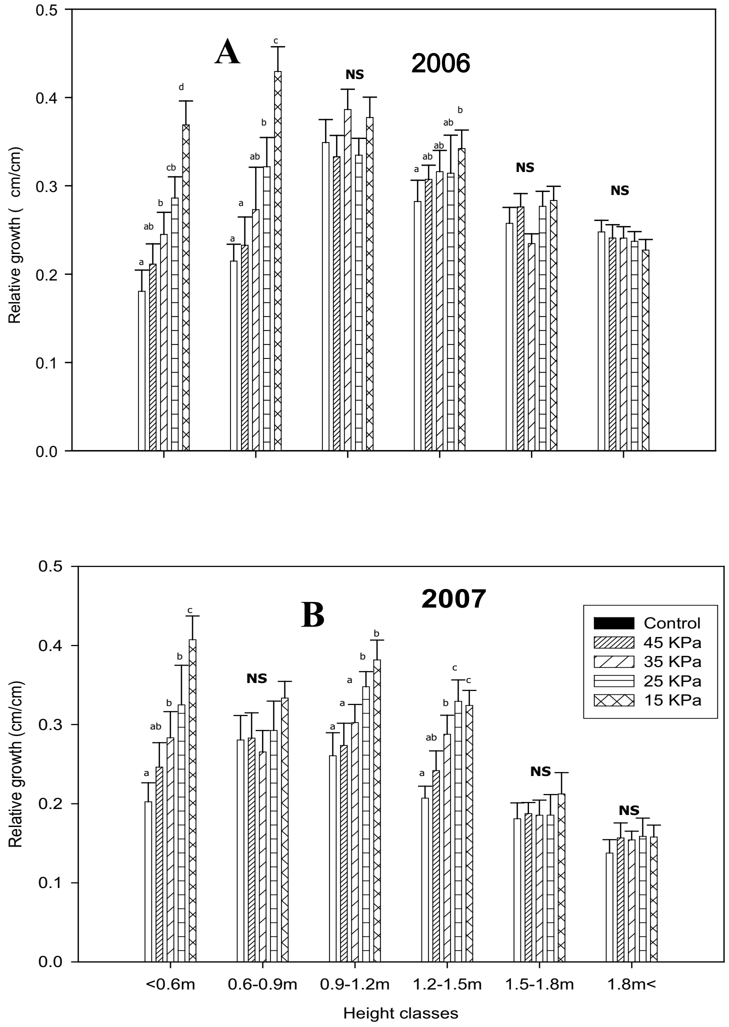

Figure 5: Mean relative height growth (cm/cm) by height classes in 2006 (A) and 2007 (B) in Horton. Similar letters indicate no significance between treatments means ($P< 0.05$)

Problems and considerations

Although an automated irrigation system should be much less problematic than a manually controlled system, there are still a few areas of concern that should be considered. Tensiometers need to be installed and removed at the beginning and end of each growing season if freezing winter temperatures are expected. We observed a tendency for the tensiometers to have a break in vacuum and no communication between the ceramic tip and the vacuum gauge. This was commonly due to dry conditions requiring a refill of the tensiometer. Sometimes, the break in vacuum was caused by leaks in connection requiring the adjustment or replacement of the 'O' ring sealing the connection between the ceramic tip and the tensiometer tube. Furthermore, poor contact between the ceramic tip and the soil also led to erroneous readings, and it was necessary to change locations and reinstall the tensiometer.

Tensiometers also have a tendency to fail in very dry soils. If an irrigation plan calls for excessive drying between irrigation events, other soil moisture measurement instruments such as TDR should be considered. Also, soil tension reported is only true for the location the tensiometer is present, emphasizing the importance of instrument placement. Tensiometer placement relative to emitters should be similar in relation to emitter spacing for the trees. Aside from tensiometer functionality, care should be taken in securing exposed wire connections. The data logger and controllers experienced few problems in both of our research locations. Periodically, the data collected produced errors, but few data points were missing or erroneous. This was more likely to occur when the frequency of data collection was increased. Using wireless data acquisition, connecting quickly and maintaining a long connection was often problematic, due to intermittent cellular coverage in the area where the data logger and modem were placed. For this reason, it is advisable to check which wireless carriers offer the strongest coverage in the area to be irrigated.

CONCLUSION

An automated irrigation system providing water on-demand was designed and constructed at two Christmas tree farms in Michigan. Elements of the system included datalogging equipment, an irrigation controller, and a set of tensiometers used as trigger for the irrigation of the various zones. The system generally functioned properly with irrigation events starting immediately as soon as the soil water tension reached the pre-determined threshold for each irrigation zone. Growth data collected indicated that low soil matric potential setup (values of 15KPa and 25 KPa) significantly improved height and basal area growth of *Abies fraseri* trees of less than 1.2 m in height. Results were more variable for trees of 1.2 m in height or higher, indicating their greater ability to withstand droughty conditions probably due to their more extensive and far reaching root system. However, there were several challenges associated with the extensive wiring required to setup such a system, proper design of computer programs needed to operate all sensors and controllers used for the system, as well as maintenance of tensiometers for accurate reading of soil moisture tension. Experiences from this project indicate that it will be challenging to implement such a system in large scale commercial operations without the active support of qualified irrigation technicians.

ACKNOWLEDGEMENT

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Appendix 1: Wiring diagram for CR1000, AM16/32 and Tensiometers

WIRING FROM CR1000 TO AM16/32	
CR1000	**AM16/32**
RES	C4
CLK	C5
GND	GND
12V	12V
COM ODD H	3H
COM ODD L	3L
COM EVEN H	EX2
COM EVEN L	SE 7

AM16/32 TO CURS100 WIRING (AM16/32 BANKS 1 – 10)	
AM16/32	**CURS100**
ODD H	H
ODD L	L
GROUND	GROUND
EVEN H	NOT USED
EVEN L	NOT USED

CURS100 TO TENSIOMETER WIRING	
CURS100	**TENSIOMETER**
H	SIGNAL RETURN
L (JUMPER WIRE TO G)	N/A
G (JUMPER WIRE TO L)	N/A
12VDC SIDE OF TENSIOMETER TO 12VDC SUPPLY	

Appendix 1: First page example of computer program used

```
'CR1000
SequentialMode

'Declare Variables and Units
Dim LCount_11
Public Batt_Volt
Public SlrkW
Public SlrMJ
Public WS_mph
Public WindDir
Public AirTF
Public RH
Public Rain_in
Public Irr_cBars(11)
Public CD16Source(16) As Boolean

Units Batt_Volt=Volts
Units SlrkW=kW/m²
Units SlrMJ=MJ/m²
Units WS_mph=miles/hour
Units WindDir=Degrees
Units AirTF=Deg F
Units RH=%
Units Rain_in=inch
Units Irr_cBars=cBars

'Weather data
DataTable(syd_30mn,True,-1)
  DataInterval(0,30,Min,10)
  Average(1,SlrkW,FP2,False)
  WindVector (1,WS_mph,WindDir,FP2,False,0,0,0)
  FieldNames("WS_mph_S_WVT,WindDir_D1_WVT,WindDir_SD1_WVT")
  Average(1,AirTF,FP2,False)
  Sample(1,RH,FP2)
  Totalize(1,Rain_in,FP2,False)
EndTable

DataTable(syd_60mn,True,-1)
  DataInterval(0,60,Min,10)
  Totalize(1,SlrMJ,IEEE4,False)
  WindVector (1,WS_mph,WindDir,FP2,False,0,0,0)
  FieldNames("WS_mph_S_WVT,WindDir_D1_WVT,WindDir_SD1_WVT")
  Maximum(1,AirTF,FP2,False,True)
  Average(1,AirTF,FP2,False)
  Sample(1,RH,FP2)
  Minimum(1,AirTF,FP2,False,True)
  Totalize(1,Rain_in,FP2,False)
  Minimum(1,Batt_Volt,FP2,False,False)
EndTable
```

Assessment of Drip Irrigation in Morocco

Abdel F. Berrada[1]

Abstract

Faced with chronic water shortages, the government of Morocco put forth an ambitious plan to equip 700,000 ha or 50% of the total irrigated land in Morocco with drip irrigation by the year 2022. Most of this acreage would be achieved by converting from inefficient flood irrigation methods to drip irrigation. The main tool used to encourage growers to adopt drip irrigation is a government subsidy that covers 60% of the total initial investment cost. Approximately 163,000 ha were equipped with drip irrigation at the end of 2008. Most of this acreage belonged to medium or large land owners and most of it was in horticultural crops, particularly fruit trees. Smaller farmers were less likely to convert to drip irrigation due to its high investment cost, the difficulty to obtain loans (the subsidy money is not disbursed until after project completion), or non-familiarity with drip irrigation. Other constraints include illiteracy, type of crops grown, and the subsidy approval process, which was lengthy and cumbersome. In order to reach its target, the government plans to convert large blocks of land to drip irrigation. It will build the infrastructure to bring pressurized and filtered water to the farms but each farmer will be responsible to equip his/her land with drip irrigation and receive the 60% subsidy. Additional incentives (e.g., greater subsidy, trust funds to guarantee loans to small farmers, etc.) may be needed to convince farmers (mostly small land holders) to sign on the program. Many are not convinced that drip irrigation would work or be profitable for crops such as wheat, barley, or alfalfa. All the drip irrigation installations I visited were surface drip irrigation systems whereby driplines were laid on the soil surface, which may interfere with field operations. Most were designed and installed by consultants or irrigation companies with little grower's participation. The average cost of a drip irrigation system in the plain of Tadla was $5,737/ha and varied with farm size, crops grown, and degree of sophistication. Approximately 70% of the farms equipped with drip irrigation had a water storage reservoir. Water reservoirs allow growers to store their surface water allocation, which they receive every two to four weeks and thus be able to use it on a more frequent basis with their drip system. Even growers who only have access to ground water (most use both surface and ground water to meet crop demand) build water reservoirs to add flexibility to their operation and qualify for the maximum subsidy amount. There is the concern that the development of drip irrigation on a large scale would further deplete ground water, which has been used extensively in the last 20 years to supplement surface water.

Drip irrigation is not a panacea but may be the best hope to conserve irrigation water in Morocco and maintain or enhance agricultural productivity (produce more with less water). It may not be feasible for every situation; therefore efforts to improve existing irrigation methods should be pursed. Moreover, Morocco should step up research and outreach programs to assist growers and consultants design and manage drip irrigation systems adapted to the social, economic, and agro-climatic conditions in the country.

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Introduction

Morocco has a Mediterranean-type semi-arid to arid climate with large fluctuations in precipitation amounts. It has experienced frequent droughts, which, along with aging infrastructure, rapid population growth, and the expansion of its economic and industrial base has led to water shortages, some severe. For example, in 2000-2006 only 55 to 60% (on average) of the demand for irrigation water was met from the main storage reservoirs (MADRPM-1, 2008). Still, there is the perception that agriculture "wastes" water since approximately 81% of the total irrigated acreage in flood-irrigated (Table 1) using traditional methods such as the "Robta" (Fig. 1 & 2), which involves furrow flooding over a series of small basins (TRM, 1999). It is estimated that with the Robta, only about half of the water that enters the field is used by the crop. The other half is "lost" mostly through deep percolation below the root zone. An additional 15 to 20% of the water is lost during transit from the dam to the field. Several methods to increase flood-irrigation efficiency have been introduced but their adoption by farmers remains low due to factors such as the relatively high cost of land leveling.

Table 1: Lands equipped for irrigation in Morocco

Irrigation Category*	**Irrigation Type (ha)**			**Total (ha)**
	Surface¶	**Sprinkler**	**Drip**	
'Grande Hydraulique' (GH)	533,900	113,800	34,900	682,600
'Petite et Moyenne Hydraulique' (PMH)	327,200	6,900	-	334,100
'Irrigation Privée' (IP)	317,600	16,950	106,900	441,450
Total	**1,178,700**	**137,650**	**141,800**	**1,458,150**
%	81	9	10	100

Source: PNEEI (2007)

¶Surface irrigation usually refers to flood- or furrow irrigation.

*GH refers to large irrigation projects and PMH to medium and small irrigation projects built by the government. IP refers to private irrigation outside the government-sponsored projects.

Figure 1. Furrow irrigation in the plain of Tadla

Figure 2. Typical Robta basins

In 2007, the government issued an ambitious plan ('Plan National de l'Economie d'Eau d'Irrigation' or PNEEI) to conserve in excess of 510 million cubic meters of irrigation water per year (MADRPM-2, 2007). The main premise of PNEEI is that past and current measures to conserve water in agriculture such as the revamping of existing irrigation infrastructure and the introduction of improved irrigation methods (e.g., sprinkler irrigation) are not sufficient to address water shortages. The goal of PNEEI is to equip approximately 555,000 ha of irrigated land with drip irrigation[2] from 2008 through 2022 (Table 2). Most of this acreage would be achieved by converting land that is currently irrigated with traditional methods such as the Robta to drip irrigation. At the end of 2008, approximately 163,000 ha were drip-irrigated, mostly in the 'IP' zones, which would bring the total acreage equipped with drip irrigation to 700,000 ha by 2022. PNEEI predicts water savings of 20 to 50% and crop yield gains of 10 to 100% compared to other irrigation methods.

Table 2. Land to be converted to drip irrigation from 2008 to 2022[3].

Irrigation zone/type	**Total irrigated land (ha)**	**Land (ha) to be converted--**	**% of Tot**

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[2] The exact term used in PNEEI is 'irrigation localisée', which could encompass other forms of micro-irrigation but appears to refer mainly to drip irrigation.

[3] Differences in irrigated acreage between Tables 1 and 2 may be due to the fact that not all the land equipped for irrigation is actually irrigated plus some irrigation projects may have been abandoned, scaled down, or not yet completed.

					al irrigated land
		Collectively	**Individually**	**Total**	
PIT	109000	49040	39700	88740	81
Total GH	670430	217940	177150	395090	59
Private irrigation	441400	0	160000	160000	36
Grand total	1111830	217940	337150	555090	50

Source: PNEEI (2007)

Eighty one percent of the total estimated cost of PNEEI of approximately $4.6 billion (One US $ = 8.0 Moroccan Dirhams) would be financed by the government, mostly through subsidies (Belghiti, 2005). Subsidies were increased from 30% of the cost of some (early subsidies) or all drip irrigation equipment and installation (plus the excavation of wells) in July 1986 to 60% in October 2006. Landowners who do not meet certain conditions may only receive the 30% (40% in dry regions) subsidy plus, since 1999, a bonus of $250 for each hectare of land equipped with drip irrigation (Belghiti, 2005; MADRPM-3, 2008). Payments at the 60% rate cannot exceed $4500/ha if a water storage reservoir is built and $2750/ha if it is not. Additional subsidies are provided for farm equipment, improved seeds and tree seedlings, etc. The procedure for applying for and obtaining government subsidies has been simplified and streamlined.

To a non-specialist, the goal set by PNEEI to equip half of the irrigated land with drip irrigation is daunting but Morocco has a long history of developing and managing large-scale irrigation projects. I will discuss some of the rewards and challenges of PNEEI, particularly in the plain of Tadla.

Main features of the study area

The area I visited the most is the Tadla Irrigated Perimeter or PIT (Fig. 3), which is one of nine large-scale agricultural irrigation districts developed by the government of Morocco to enhance food production, create jobs, and store and manage water. Water is conveyed to PIT farms from two main reservoirs, Bin El Ouidane and El Hansali via approximately 3000 km of canals (Fig. 4). The total gravity-fed area is around 100,000 ha and is home to 27,000 farmers. Additional lands (≥8500 ha) are irrigated exclusively with well water outside the zone 'GH'. Surface water is allocated to blocs of land by ORMVAT ('Office Regional de Mise en Valeur Agricole de Tadla), after consultation with stakeholders, based on available supplies and the crops grown. Priority is usually given to fruit trees, sugar beets, and forage crops. However, each farmer is free to manage his allotment based on his needs. Water is delivered on a rotational basis or 'Tour d'Eau' every 2 to 4 weeks.

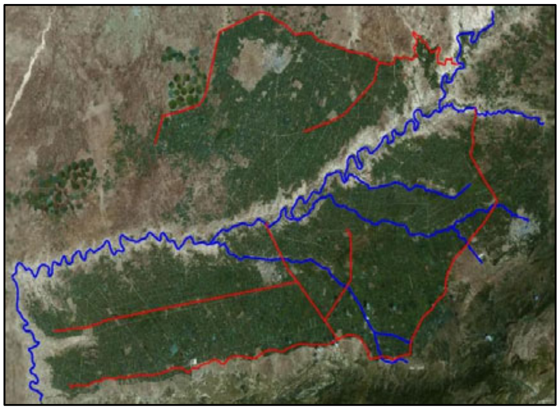

Figure 3. Satellite view of PIT composed of two main irrigation zones, Beni Moussa and Beni Amir. Source: ABHOER.

Figure 4. Raised irrigation canal at PIT. Source: ORMVAT

Annual natural precipitation averaged 268 mm from 1970 through 2007 with a downward trend (Fig. 5). Less than 50% of the water required to meet crop water demand was supplied from Bin El Ouidane or El Hansali in 1996-2008 (Fig. 6&7). The deficit is partly made up with groundwater, which has been tapped extensively in the last 20 years. Hammani and Kuper (2008) reported the existence of 8310 active and inactive wells within PIT and over 4500 wells outside the zone of action of ORMVAT. This could have serious consequences for water supply and management in the Oum er Rbia river basin.

Figure 5. Annual rainfall at PIT-Ouled Gnaou. Source: ORMVAT

the '3' in 'Mm3' should be superscripted

part isn't showing of the year "1991-..."

this sum is over 100%

DEFICIT of 43%!

Figure 6. Water allocation for Beni Amir
from 1996 to 2008
(Source: ORMVAT)

DEFICIT of 45%!

Figure 7. Water allocation for Beni Moussa
from 1996 to 2008
(Source: ORMVAT)

Accomplishments

Approximately 10,700 ha were equipped with drip irrigation at PIT from 1991 through 2008 (Fig. 8). There was a jump in drip-irrigated acreage in 2003 and in 2007 due to increases in government subsidy.

the '3' in 'Mm3' should be superscripted

part isn't showing of the year "1991-..."

this sum is over 100%

Figure 8. Cropland equipped with drip irrigation in PIT in 1991-2008. Source: ORMVAT.

Unofficial ORMVAT data (Table 3) indicate that at least 80% of the acreage approved to receive the drip irrigation subsidy from July 2002 through November 2008 was earmarked for fruit trees (mostly citrus). This makes sense for several reasons:

- Citrus fruits are among the most profitable crops (Daoudi, 2008)
- Drip irrigation is generally cheaper and easier to install and manage in orchards than for non-tree crops such as alfalfa or sugar beets, partly because it does not require as many driplines.
- Growers who install new orchards or replace old trees with new ones get a subsidy of $975/ha. This is in addition to the drip-irrigation subsidy.
- Citrus orchards generally represent medium to large acreages and often belong to well-to-do and/or progressive landowners with a greater ability to finance their land improvement projects than smaller farmers do.

Table 3. Drip-irrigation subsidy requests approved by ORMVAT from July 2002 through November 2008, sorted by crop. Source: ORMVAT.

Crop	No. requests	Total SAU ha	SAU/request ha	Investment cost* $/ha	Subsidy $/ha	Subsidy/Cost %
Roses	5	147	29	4331	1826	42
Olive	24	670	28	4962	2862	58
Pomegranate	4	36	9	4991	2153	43
Citrus	218	3958	18	5721	2907	51
Field crops	3	45	15	6082	3649	60
Vegetables	44	547	12	6387	3352	52
Other	21	374	18	6494	3829	59
Vineyard	3	15	5	12016	3550	30
Total/w. average	**322**	**5791**	**18**	**5725**	**2979**	**52**

*One US dollar = 8.0 Moroccan dirhams

Bekkar et al. (2007) reported similar results, i.e., 83% of the drip-irrigated land surveyed consisted of citrus orchards. Only 8% had vegetable crops. The average size of the completed drip irrigation projects (sample size: 21 farms) was 12.8 ha. It was 18.0 ha when averaged over all the approved subsidy requests in 2002-2008 (Table 3). Fifty two per cent of the approved requests were for projects of 10 ha or less in size but represented only 16% of the total acreage. In contrast, projects of 20 or more hectares in size represented 26% of the requests but accounted for 66% of the total acreage (Table 4).

Table 4. Drip-irrigation subsidy requests approved by ORMVAT from July 2002 through November 2008, sorted by land size. Source: ORMVAT.

Size category ha	No. requests	Total land ha	Hectares/ request	Investment cost* $/ha	Subsidy $/ha
Less than 10	169	915	5	6159	2921
10 - 19.9	71	1047	15	5578	2903
20-49.9	63	1878	30	5416	2723
Over 50	19	1951	103	5899	3293
Total/w. average	**322**	**5791**	**18**	**5725**	**2979**

*One US dollar = 8.0 Moroccan dirhams

The average estimated initial drip irrigation cost was $5,725/ha, with large variations within and between years, crops, and individual requests. The cost generally decreased as the number of hectares increased but not always. Kobry and Eliamani (2005) reported average estimated investment costs of $7,500/ha for approved drip irrigation projects of less than 5 ha, $6,750/ha for 5 to 10 ha, and around $3,950/ha for 10 ha or more. They did not distinguish between projects that had a water storage reservoir and those that did not. Daoudi (2008) reported the following initial investment costs for citrus orchards at PIT: $6,500 to $6,875/ha for orchards of 10 ha or less and around $5,000/ha for orchards greater than 10 ha in size. He estimated the net profit margin for an orchard in full production at $5,739/ha with drip irrigation compared to $3,053/ha with flood irrigation.

Examples of drip irrigation system component costs reported in subsidy requests submitted in late 2008 are shown in Table 5. They ranged from $3,733/ha to $8,837/ha. The head station and water delivery system accounted, on average, for 63% (45-65%) of the total system cost while the water storage facility represented about 20% (18-36%) of the cost.

Table 5. Estimated drip irrigation system component costs of five projects submitted to ORMVAT in 2008.

Project No.	**1¶**	**2**	**3¶**	**4**	**5**	**Cost/ha**	**% of total cost**
System component	**Estimated cost ($)**						
Head station & water delivery	92,088	82,500	148,833	18,660	514,255	**4,062**	**63%**
Storage reservoir	36,399	40,433	60,073	14,916	139,155	**1,380**	**21%**
Pumps	30,413	4,375	7,695	2,813	106,969	**722**	**11%**
Shelter for the head station	5,714	11,198	9,636	4,979	30,128	**292**	**5%**
Total cost	**164,614**	**138,505**	**226,237**	**41,367**	**790,507**	**6,457**	**100%**
Land Area (ha)	25.4	37.1	25.6	4.7	118	210.8	
Cost/ha	**6,481**	**3,733**	**8,837**	**8,801**	**6,699**		
Reservoir Capacity (m^3)	7500	7600	7200	1920	37000		
Crop	Citrus	Citrus	Sugar beets	Citrus*	Citrus**		

¶ Projects 1 & 3 were designed by the same company.

*Citrus trees and vegetable crops

**Citrus trees and sugar beets

Most of the farms I visited had all the essential components of a modern drip irrigation system such as filtration, chemigation, flowmeters, control valves, and the option to run the system automatically (Fig. 9 & 10).

Approximately 70% of the subsidy requests approved by ORMVAT from July 2002 through November 2008 had storage reservoirs of varying sizes (Unpublished data). The rest either didn't have a water reservoir or the information was missing. Storage reservoirs are recommended even when the sole source of water is groundwater. They provide a buffer in case of well pump malfunction or other unforeseen circumstances. Storage reservoirs are even more critical when surface water is the main or only source of irrigation water. This is because surface water (e.g., from Bin El Ouidane) is allocated every two weeks or longer, depending on availability, which can cause water stress even for flood-irrigated crops. With drip irrigation, water should be applied frequently (e.g., daily during peak demand) to meet crop demand.

The newer drip irrigation installations (e.g., since 2007) were likely to have a water reservoir due to the substantial subsidy (up to $4,500/ha) provided by the government. There was a significant correlation ($r^2 = 0.63$) between reservoir size and drip-irrigation acreage (Unpublished data). Sizing of the water reservoir should be done based on the number of hectares to be irrigated and surface water availability (e.g., flow rate and 'tour d'eau'). Daoudi (2008) recommended a storage capacity of 432 m^3/ha for citrus orchards in PIT based on a water allocation of 4 h/ha at 30 l/s or 6 h/ha at 20 l/s. Growers who rely heavily on surface water may want to build reservoirs with more storage capacity (≥500 m^3/ha).

All the water reservoirs I visited were lined with a polyethylene geomembrane to prevent water seepage (Fig. 9). Kobry and Eliamani (2005) reported that the cost of the geomembrane exceeded 50% (in three-quarters of the approved projects) of the total reservoir cost. Daoudi (2008) reported reservoir costs of \$3.75 to \$5.00/m^3 for citrus orchards.

Reservoirs not only provide a buffer so that crop water needs can be met on a timely manner. They also allow sediments to settle down, thus reducing water filtration requirements. This was less of a concern than algae, which given enough sun and nutrients (e.g., N and P) multiplies rapidly and can plug up screens and cause pumps to fail. The most common control method used was an algae-eating fish called 'carpe chinoise' (Chinese carp).

Figure 9. Water storage reservoir lined with a geomembrane. PIT, March 2009

Figure 10. Disk filters. PIT, March 2009

Approximately 42% of the drip irrigation subsidy requests approved in 2002-2008 at PIT listed groundwater as the sole source of water (Unpublished data). Most drip-irrigated farms/fields had access to both surface and groundwater. Only two of the farms I visited used well water sparingly, due to its high salt content. When they did, they mixed it with surface water, which was less salty.

Only one of the 17 farms I visited had flexible drip tubing, commonly referred to as drip tape in the USA. All the other farms had solid round drip tubing. None of the installations had buried drip tapes. This makes sense for tree crops such as oranges and olives because generally, the drip tubes are laid out along the tree rows and away from vehicular traffic. For less permanent and more densely planted crops such as wheat, alfalfa, or sugar beets, laying the drip tubes on the soil surface will get in the way of field operations such cultivation and harvest (Fig. 11). Thus the driplines may have to be moved to the side or rolled back every time one has to cut alfalfa for instance.

Citrus orchards usually have two driplines per tree row (one on each side of the tree), although some farmers do not install the second dripline until the trees are few years old (Fig. 12). The most common spacing between emitters was 0.75 m and the most common emitter flow rate was 3.9 l/h. Growing crops such as melons or sugar beets or even alfalfa between the citrus trees appeared to be a common practice in new orchards equipped with drip irrigation. This was done to generate income until the trees started producing marketable fruits. Dripline spacing in sugar beet fields commonly ranged from 0.8 to 1.2 m with 0.4 m between emitters and 2 l/h flow rate.

Figure 11. Hoeing of a sugar beet field fitted with drip tubes. Ouled Gnaou, December 2008

Figure 12. Drip-irrigated sugar beet in a young citrus orchard in PIT. January 2009

Intercropping may hinder tree growth, particularly when water is in short supply, but can suppress weeds and provide nutrients when used as a cover crop or green manure for example. These practices were not observed at PIT. Often, weeds are pulled from crop fields and fed to livestock or grazed anywhere they can be found (fallow ground, ditches, road sides, along irrigation canals, etc.).

Most of the drip irrigation installations I visited were designed by private companies or consultants. More often than none, the company that designed the drip system also installed it or subcontracted parts of it to other companies (turnkey projects). This could create a conflict of interest if, for example, the design company supplies its own equipment, which may not be as good or as affordable as other equipment available on the market. There did not seem to be much grower input in the project design and limited involvement in its installation. In the farms I visited, some works (e.g., trenches for the PVC pipes) and some structures such as the shelter that houses the head station or the fence around the storage reservoir were built by property owners or their hired hands.

Collective projects

Individual drip irrigation projects at PIT averaged a little over 1,000 ha/yr from 2002 through 2008 (Fig. 8). At this rate, it would take a long time to reach the goals set by PNEEI. It is believed that farmers who have taken advantage of the government subsidies are generally well-connected, well informed, and have access to capital. Moreover, most of the land converted to drip irrigation consists of citrus orchards, which represent about 10% of the total irrigated acreage at PIT[4]. In contrast, wheat, barley, alfalfa, and sugar beets occupy 69% of the irrigated acreage and are the staple crops for small farmers. Cognizant of these facts, the government plans to convert approximately 218,000 ha collectively, of which 49,000 are located at PIT (Table 2).

Collective projects or ‘projets collectifs’ will make it easier for small farmers to convert to drip irrigation, since the government will build the infrastructure to bring pressurized (and filtered) water to each farm. Therefore, individual farmers will not have to build storage reservoirs for example, which would lower the cost of the drip system[5]. Each farmer will be entitled to the 60% subsidy to equip his or her land with drip irrigation. Construction of collective projects is expected to start in 2011.

In a study funded by the World Bank, an area of about 20,000 ha in Beni Moussa West was identified based on the fact that the drop of elevation from the water source would generate enough pressure to operate the drip irrigation system without additional energy input. It was later narrowed down to 10,000 ha and then to approximately 3,700 ha. This area was selected for a pilot project based on the large number of wells[6], good groundwater quality, and growers’ enthusiasm for the project. There were conflicting reports as to whether the pilot project will be built first before the whole area of 20,000 ha is converted to drip irrigation.

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[4] The irrigated acreages for the 2009/2010 season were as follows: Wheat & barley: 34,000 ha; Alfalfa: 22,000 ha; Sucre beet: 13,000 ha; Citrus trees: 9,500 ha, Olives & other fruit trees: 16,500 ha, Summer corn/maze: 12,000 ha. Source: ORMVAT

[5] Apparently attempts to build storage reservoirs for groups of farmers or farmers’ cooperatives have not been too successful at PIT, unlike in other irrigated perimeters such as Souss-Massa or Moulouya. However, there were plans to equip two growers’ cooperatives totaling 265 ha with drip irrigation in 2008.

[6] There were 287 deep wells, 467 shallow wells, and 69 intermediate wells on 3183 ha of land.

Fifty percent of the acreage in the pilot project area was made up of farms smaller than 5 ha in size and 10% of farms > 20 ha. Cropping systems were dominated by cereal (wheat and barley) crops, alfalfa, and sugar beets (Table 6). When this area is converted to drip-irrigation, it is expected that the acreage in wheat, barley, and alfalfa will decrease while that of fruit trees (citrus and olive) and vegetable crops will increase and corn silage would be the forage of choice (SCET-SCOM, Personal Communication, January 2009). The projected cropping system would preserve PIT's vocation as a major milk and sugar producer but would enhance profitability by increasing the acreage of horticultural crops.

Water requirements[7] (Table 7) were calculated using Penman-Monteith reference ET and crop coefficient estimates from FAO's Irrigation and Drainage Paper No. 56 (Allen et al., 1998).

Table 6. Current (2008) and projected crop acreage in the pilot project area.

	Current hectarage	**Projected**	
Crop	**ha**	**%**	**%**
Cereal crops	1312	32	25
Alfalfa	742	18	10
Corn silage	0	0	15
Sugar beets	667	16	18
Citrus*	317	8	15
Olives	252	6	15
Vegetable crops	152	4	10
Total (ha)	**3445**		
Cropping intensity (%)			

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[7] Several subsidy requests I examined based the drip irrigation system design on peak water demands of 5 mm/day for citrus trees and 7 to 8 mm/day for sugar beet.

108the '3' in 'Mm3' should be superscripted

part isn't showing of the year "1991-..."

this sum is over 100%

*92 ha were drip-irrigated. The total drip-irrigated acreage in the pilot project area was 111 ha in 2008

Table 7. Monthly drip irrigation water requirements (at the field level) for the pilot project.

Cropping System	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Total**
	Water requirement (m^3/ha)												
Current	323	143	85	14	54	142	337	514	642	509	460	431	3654
Projected	376	184	89	17	49	128	319	586	867	864	900	840	5219
Rainfall (mm)	8.2	26.8	50.9	45.2	41.5	40.8	47.9	46.3	23.7	5.4	0.9	2.8	340

The annual drip irrigation water requirement for the projected cropping system was estimated at 5219 m^3/ha at the field level and 7223 m^3/ha at the distribution reservoir, which is about the average water allocation (7163 m^3/ha) for Beni Moussa. Water savings will result from increased irrigation efficiency. Calculations were based on the following efficiencies: From Bin El

Ouidane to the distribution reservoir: 85%, open water channels: 85%, buried water pipes: 95%, field (drip irrigation): 90% (SCET-SCOM, Personal Communication, January 2009).

Before the government would start construction of the pilot project, at least 70% of farm owners/managers must sign a commitment to convert to drip irrigation within two years of completion of the infrastructure (e.g., filtration and pumping stations and water delivery system) that would bring pressurized water to their properties. The project cost was estimated at approximately \$5,000/ha to bring pressurized water to each farm and another \$3,750/ha to equip it with drip irrigation.

Challenges:

Getting farmers to agree to, help pay for, or manage shared irrigation structures can be a challenge. As one company representative put it,

"Farmers are individualistic and competitive by nature. They may copy a neighbor's innovation but they will fight over borders, status, and water!"

Several concerns about the pilot project in particular and collective projects in general were raised at growers' meetings. They included:

- The ability to finance drip irrigation installation at the farm level, given the large number of small farms (about 80% are < 5 ha). This is exacerbated by the fact that farmers do not receive the subsidy money until after the project is completed. Farmers were also worried about having to pay for the infrastructure to bring pressurized water to their land[8].
- Land ownership. Most farms in Morocco have multiple owners due to inheritance laws, which makes it difficult to agree on land improvements, especially if the improvements require a substantial investment.
- Farms are often made up of scattered fields of various sizes, some tiny. Only the fields located in the selected irrigation blocs will be considered for conversion to drip irrigation.
- Even though each farmer will have his/her own water intake valve, some degree of coordination may be required among farmers within each irrigation bloc.
- Farmers worried that water prices would go up as a consequence of this project, which is likely. In 2008, the water user fee at PIT was \$0.03/m^3. Drip-irrigation pumping costs were estimated at \$0.06/m^3 at the storage reservoir (located on the farm) and \$0.10/m^3 at the well (Daoudi, 2008). There have been attempts to structure water fees so that farmers who "waste" water are penalized but this has not been applied due to accounting difficulties, water shortages or other reasons.
- Water availability was a major topic of discussion. Would farmers who adopt drip irrigation be guaranteed a fixed/adequate water allocation? What would happen to the saved water? Would water be available at all times?

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[8] Agricultural producers help pay for the irrigation infrastructure and associated services provided by ORMVAs in two ways: (1) water user fees (in effect), and (2) construction fees to recover 40% of the initial investment to build the irrigation infrastructure. The latter is payable over 17 years at 6% interest with a grace period of four years.

  - How would drip irrigation work for subsistence crops such as wheat and barley? Would I have to remove the drip tubes every time I need to work the field or harvest the crop? Would it cost too much?
  - Potential over supply of high value crops

There were many more questions and not enough satisfactory answers. Some of the concerns stemmed from non-familiarity with the subsidy program and the lack of information about drip irrigation in the region. A number of attendees saw drip irrigation being used in citrus orchards but they were not convinced that it would work for their crops or be economically feasible. Options that were adopted or considered by the government to ease the financial burden on small farmers willing to adopt drip irrigation include:

- A fund to guarantee loans to needy farmers
- Increase in drip irrigation subsidy
- Reduction in farmers' contribution to external works

Water conservation and environmental considerations

When designed and operated properly, drip irrigation will save water compared to other irrigation systems (Table 8). Results by Bouazzama and Bahri (2007) indicate that this may not always be the case. They surveyed 23 citrus orchards in 2002 and found that the ratio of irrigation amount versus water requirement was: 0.7 to 1.5 in 39% of the orchards, 1.6 to 2.3 in 48%, and 2.6 to 2.9 in 13%. The water applied ranged from 4420 m^3 to 18610 m^3/ha (all orchards) and produced on average 3.6 kg of oranges/m^3 (4 orchards).

Table 8. Estimated water savings due to drip irrigation in PIT. Source: ORMVAT.

Crop	**Flood-irrigation**	**Drip irrigation**	**Water saved**
	m^3/ha		%
Citrus	12000	7200	40
Olive	5000	2700	46
Sugar beets	8000	4800	40
Vegetable crops*	12000	7000	42

*Two crops/yr

Chohin-Kuper et al. (listed by Petitguyot et al., 2005) reported that in several Mediterranean countries, the adoption of micro-irrigation decreased water consumption per unit area but not at the farm level since the "saved" water was used to irrigate more land. In PIT, there may not be much room for expanding the irrigated acreage, so the potential for water savings with drip irrigation is real (Petitguyot et al., 2005).

A serious concern is the impact drip irrigation would have on groundwater recharge and use. Indeed, an increasing number of agricultural producers use groundwater to supplement their surface water allocation. Hammani et al. (2005) estimated the number of wells in PIT at around 10,000. Groundwater use accelerated in the 1990s due to drought and generous government subsidies. Furthermore, irrigation return flows accounted for 80% of the aquifer recharge in the plain of Tadla (Hammani and Kuper, 2008). Thus, the more flood-irrigated land is converted to drip irrigation, the less water would be returned to the river and its aquifers, which could result in further groundwater depletion, increased pumping costs and could trigger more restrictions on groundwater use[9]. Conversely, increased irrigation efficiency would narrow the gap between water supply and crop water requirements and thus reduce the need for groundwater. However, current government policies (e.g., subsidies for irrigation improvement or extension which include well excavation) seem to favor property owners who have access to groundwater.

Another concern is groundwater quality given the relatively elevated salt concentrations in some areas such as the Beni Amir (ORMVAT, 2008). Drip irrigation would reduce leaching of salts to the groundwater but can result in salt accumulation in the root zone over time (Berrada, 2006). This could be alleviated by mixing groundwater with surface water which is generally not as salty as groundwater or by flushing out the salts occasionally with large water applications.

Procedure for obtaining the government subsidy

In 2002, the regional agricultural services such as ORMVAT started reviewing the subsidy requests to make sure that the drip irrigation projects were designed and installed properly. In addition, a “Guichet Unique” or clearing house was created in 2008 within each service to streamline the application procedure for all ag-related subsidies and speed up project review and approval. This was in response to customers’ complaints, abuses of the subsidy system, or faulty drip irrigation design by inexperienced or unscrupulous consultants and irrigation companies. Prior to 2002, the regional agricultural credit banks (CRCA) not only provided loans and subsidy money to eligible farmers but also monitored the irrigation project execution.

Subsidy seekers generally submit two documents, one to ORMVAT (DPA outside ORMVA’s jurisdiction) and the other to CRCA or to a private bank to request a loan to finance the project since the subsidy money is not disbursed until after the project is completed. After receipt of the request, Guichet Unique and other designated staff have a total of 28 days to review, approve, and monitor the irrigation project and notify CRCA of its successful completion and the amount to be disbursed to the applicant. In turn, CRCA has two days to issue a check to the subsidy recipient.

The review and approval process can be delayed due to missing or invalid information, faulty design, or other irregularities. The applicant is notified in writing of such problems and asked to address them. He/she cannot start installing the project until the subsidy request is duly approved. Growers have the option to request the subsidy after they install the drip irrigation system, in which case they are only entitled to 30% (40% in dry areas) of the system’s cost plus a bonus of $250/ha. They may choose this option to avoid lengthy delays or for other reasons such as questionable land ownership or illegal use of groundwater. In the late 1990s landowners were given a grace period of three years to declare wells that were excavated before 1995 without proper authorization. Apparently many did not due to ignorance or mistrust.

Despite marked improvements, the subsidy request is still cumbersome. In my opinion, too many people are involved in the approval process and too many details/documents are required, which makes it difficult for the average farmer (often illiterate) to apply thus, the booming

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[9] Laws to regulate groundwater use such as the requirement that users install flow meters at their wells and report the volume of water pumped have not been enforced. There are also indications that non-authorized excavations and use of well water still abound.

business of consultants doing everything from project initiation to its completion, 'clé en main'. Furthermore, there are no clear standards by which to compare prices, a lack of transparency (e.g., service fees were often embedded with materials costs) and possibly not enough warranties to ensure the system's longevity.

Research and outreach

The design and operation of drip irrigation systems in Morocco improved over the years due to, among other things, experience, generous government subsidies, which since 2002 have been tied to a rigorous review process; and increased competition among drip irrigation consultant and supply companies. However, there is plenty room for improvement! For example, Bouazzama and Bahri (2007) reported that 43% of the citrus orchards surveyed did not have soil or leaf test results on which to base their fertigation programs. Also, there did not seem to be much guidance in scheduling irrigations other that what the original design called for. Managing drip irrigation so that it produces the expected results (e.g., water conservation and an increase in crop yield and quality) requires experience and a departure from old habits (Burt and Styles, 1999)[10]. Experience will come from increased involvement of farm owners and managers in the design, operation, and maintenance of drip irrigation. It will be reinforced by research and outreach, which needs to be stepped up to match the determination and enthusiasm with which the government of Morocco is pursuing the goals set by PNEEI.

One area where research is lacking is subsurface drip irrigation or SDI. With SDI, drip tapes should not interfere with field operations such as row cultivation or crop harvest. Another advantage is reduced water evaporation from the soil surface, the extent of which will vary depending on drip tape placement depth, irrigation depth, soil type, etc. Adequate filtration and maintenance (e.g., flushing the driplines regularly and injecting acid to dissolve mineral deposits) will keep the system running for a long time. Leaks in the drip tapes can develop due to damage from tillage implements (e.g., if the drip tape is not deep enough) or from rodents and may be a challenge to fix. SDI would be ideal in Morocco for row crops such as corn and sugar beets and even solid-seeded crops such as alfalfa and wheat but would require more management skills than non-SDI systems. SDI can be designed to accommodate several crops in rotation but research is needed to determine the optimum drip tape placement depth and lateral spacing, etc.

Conclusions and recommendations

The 2008/2009 season brought much needed relief (in the form of snow and rain) to an otherwise bleak picture of meeting the demand for water in Morocco. In 1994-2006, only 44% (on average) of the normal allocation for ag water was met nationally, due to frequent droughts, increased demand for municipal and industrial water, siltation of water reservoirs, etc. Nonetheless, agriculture still uses a large share (80 to 90%) of the available water and, by some accounts, "wastes" a good deal of it (Berrada, 2005). This is mainly because of inefficient flood-irrigation systems such as the 'Robta' that is predominant in the irrigated perimeters.

10

Unlike flood irrigation, drip irrigation requires frequent water applications (usually in small amounts); otherwise it would be difficult to catch up, i.e., meet crop water demand.

To conserve water and optimize its use efficiency (produce more with less!), the government put forth an ambitious plan by which 700,000 ha of cropland would be equipped with drip irrigation by 2022. Already 163,000 ha were fitted with drip irrigation at the end of 2008. The primary tool used to entice landowners and managers to adopt this technology is a subsidy of 60% of the drip irrigation installation cost estimated at $7,500/ha if a storage reservoir is built. The average cost (based on subsidy requests) at PIT averaged $5,725/ha from 2002 through 2008 and varied from year to year and with land size, degree of sophistication, crops grown, etc.

Over 80% of the land equipped with drip irrigation at PIT consisted of fruit orchards, which made sense economically and technically. Only recently (e.g., after the subsidy was increased to 60% in 2007) has the number of subsidy requests for non-tree crops (mostly sugar beets) picked up. In order to reach the goal set by PNEEI to equip 88,740 ha or 81% of the total irrigated land at PIT with drip irrigation, the government will build the infrastructure to bring pressurized water to 49,000 ha of cropland. This is because small farmers (80% of the farms at PIT are < 5 ha) who grow mostly wheat, barley, alfalfa, and sugar beet cannot afford drip irrigation (on their own), are not familiar with it, or are not convinced that it would work for them. These so-called 'projets collectifs' present, in my view, the biggest challenge to the government's ability to fulfill the goals set by PNEEI. The program is already popular among private landowners, particularly outside the government-sponsored irrigation projects but it could be an uphill battle to convince subsistence farmers to switch to drip irrigation. Nonetheless, the government is working diligently to bring about change in anticipation of future water shortages[11].

Drip irrigation is not a panacea but may be the best hope to conserve water and enhance agricultural productivity and sustainability in Morocco. It may not work for every situation, thus it is prudent to continue efforts to improve existing irrigation methods. Similarly, it is prudent to start small (e.g., pilot projects) before investing too much in collective projects. More importantly, property owners' and growers' associations should be allowed and encouraged to assume more responsibility in the design, installation, and management of drip irrigation projects. This would bring down the cost and ensure the project's sustainability. Finally, research and education should be stepped up to:

- Develop drip irrigation systems and best management practices adapted to the climatic, soil, social, and economic conditions of the various agricultural production zones in Morocco.
- Demonstrate the benefits of drip irrigation for various crops and conditions.
- Teach farmers how to design[12], install, and manage drip irrigation.

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[11] Recently the government of Morocco launched what is called 'Plan Maroc Vert' or 'Green Morocco' to (1) develop a modern and highly performing agriculture through private investments and, (2) enhance small-scale agriculture to combat poverty.

12

[12] This may be a challenge for older or illiterate farmers but they should at least be taught the basics of drip irrigation design and how the various components work. Moroccans farmers are smart, regardless of their degree of schooling!

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Response of Bell Pepper to Subsurface Drip Irrigation and Surface Drip Irrigation under Different Water and Nitrogen Coupling Conditions

Revised manuscript submitted to

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Abstract

Subsurface drip irrigation is a new irrigation technique. A 2-year field experiment was conducted in 2007, 2008 to investigate the response of bell pepper to subsurface drip irrigation (SDI) and surface drip irrigation (DI). Four nitrogen levels of 0, 75, 150, 300kg•ha^{-1} (N0, N75, N150, N300) comprised the fertilization treatments. The irrigation interval is 4 days. The results showed that SDI resulted in higher bell pepper yield than DI by 4% in 2007, and 13% in 2008. The water consumption of SDI is lower than of DI by 6.7% in 2007, and 7.3% in 2008. The root length densities under SDI and DI were1.46 and 2.44 times higher than that under BI (border irrigation). The percent of root length below 10 cm soil depth under SDI were higher than that under DI by 7 percentage points. The results revealed that SDI not only promote crop root growth, but also enhanced the root development downwards the deep soil depth, which could increase nitrogen uptake, reduce nitrogen leaching, increase bell pepper yield and nitrogen use efficiency. The SDI N150 treatment were recommended as the optimal irrigation and fertilization practices for improving bell pepper yield and WUE and reducing NO_3^--N leaching.

Key words: Water and nitrogen coupling; Pepper; Subsurface drip irrigation;
Surface drip irrigation

1. Introduction

The efficient utilization of available water resources is crucial since China shares 22% of the global population with only 7% of farmland and 7% of the world's water resource. So far, water shortage has become a threat to human survival. Agricultural production is the largest consumer of water, which accounts for more than 70% of the total water consumption. To meet the food security, human health and the balance of natural ecosystems, all countries paid more attention on agricultural practices to get a solution for water shortage.. Therefore , the techniques for saving irrigation water and thereby increasing crop water use efficiency (WUE) are important in China, in particular in the water-shortage regions.

Nitrogen fertilizer application rates have increased dramatically in agricultural systems in north China in recent years (Zhu et al., 2005), which resulted in nitrate leaching and groundwater contamination (Rossi et al., 1991; Barraclough et al., 1992; Cameron et al., 1997; Li et al., 2001; Zhu et al., 2004). It was reported that over fertilization in north China has led to high concentrations of nitrate in groundwater and drinking water (average of 68 mg L^{-1}) and crop recoveries below 40% of applied N in some areas (Zhang et al., 1996). It's now an urgent need to regulate irrigation and fertilization practices to ensure better distribution of soil moisture and fertilizer, so as to maximize the use of water and fertilizer, to minimize nitrate leaching and groundwater contamination and to obtain the optimal agronomic, economic and environmental benefits.

Subsurface drip irrigation, the latest method of irrigation, was developed from surface drip irrigation. Subsurface drip irrigation laterals are buried underground. Therefore, this method can supply water and nutrients to the roots as needed (Phene and Beale, 1979; Lamm, 1995; Camp et al., 1997). Compared to other irrigation systems, subsurface drip irrigation have significant advantages including more efficient water use, slight water quality decline, greater water application uniformity, enhanced plant growth, crop yield and quality, improved plant health, better weed control, improved farming operations and management, system longevity and less pest damage (Lamm, 2002). In particular,, subsurface drip irrigation systems keep the topsoil drier, which lead to fewer surface soil evaporation, lower air humidity of canopy, less disease and pest damage and deeper crop roots. Therefore, subsurface drip systems reduce crop respiration, increase photosynthesis and efficiency water and nutrients uptake, improve WUE, increase nitrogen utilization, reduce nitrate leaching, and decrease NO_3^--N pollution in groundwater (Phene, 1999).

Based on the results at the Water Management Research Laboratory over a period of 15 years, Ayars et al. (1999) demonstrated that SDI led to significant increase of yield and WUE for all crop because of the reduced deep percolation by using high frequency irrigation. Sezen et al. (2006) reported that yield and water use of bell pepper was affected by surface drip irrigation regimes. He recommended I_1K_{cp3} (interval: 3 to 6 days; K_{cp3}=1.00) irrigation regime for bell pepper in order to attain higher yields with improved quality. Using the same method in green bean production, Sezen et al. (2005) also found that the yield, WUE and Irrigation Water Use Efficiency (IWUE) were significantly influenced by the irrigation intervals and plant-pan coefficients. Howell et al. (1997) found that different subsurface drip irrigation frequencies (1day and 7days) show little effect on corn yield. Payero et al. (2008) found that irrigation amount applied with subsurface drip irrigation and envpotranspiration significantly affected corn yields. According to Mahajan et al. (2006), low irrigation amount

(0.5Ep) and low nitrogen fertilizer amount (137kg N·ha^{-1}) didn't decrease greenhouse tomato yield, but increased root length. Sensoy et al. (2007) reported that irrigation amount and evapotranspiration significantly influenced melon growth and yield under surface drip irrigation and 6days interval and Kcp=0.9 were recommended for melon production. Cabello et al. (2009) also has taken out drip irrigation experiment to investigate yield and quality of melon under different irrigation and nitrogen rates, it's reported that moderate water deficit and reduce nitrogen input to 90 kg·ha^{-1} didn't reduce crop yield. Under subsurface drip irrigation, nitrogen application also affected broccoli yield and quality (Thompson et al., 2003). However, according to Sorensen et al. (2004), low N rate (67 kg N·ha^{-1}) yield of cotton was similar to high N rate (101 kg N·ha^{-1}) for subsurface drip irrigation.

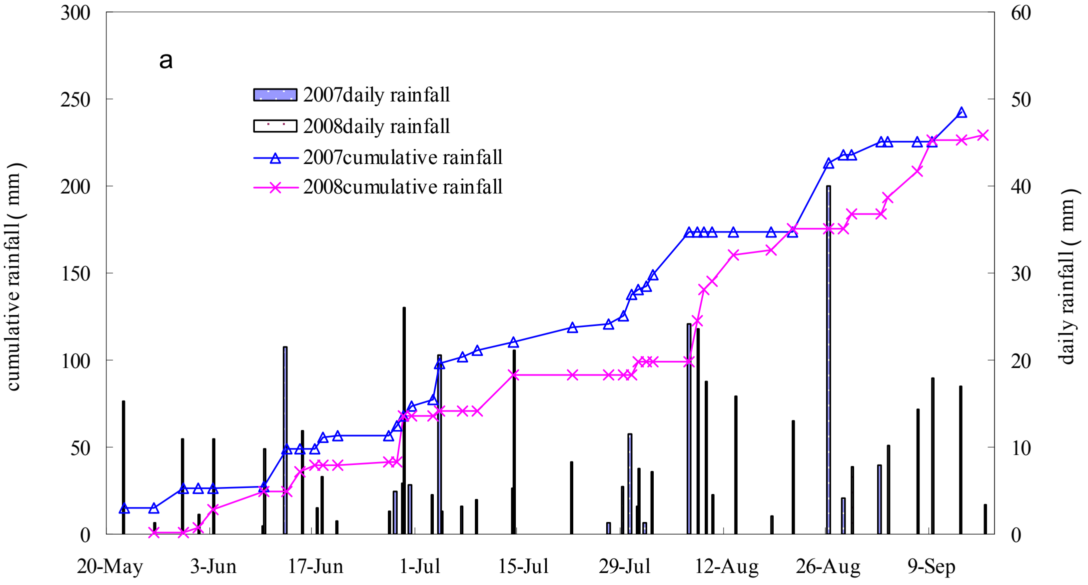
Comparative studies of subsurface drip irrigation with other irrigation systems under different water and nitrogen coupling conditions are scanty. Patel et al. (2008) has conducted a 3-years experiment to study the effect of depth of drip lateral. The results showed that the subsurface drip irrigation had higher onion yield than surface drip systems. Hanson et al. (1997) compared the lettuce yield and applied water among furrow, surface drip and subsurface drip irrigation. He found that surface drip irrigation resulted in lower lettuce yield than furrow and subsurface drip irrigation, but drip irrigation consumed only 43%-74% water amount of furrow. Hanson et al. (2004) compared subsurface drip irrigation with sprinkler irrigation and the results revealed that subsurface drip systems could increase tomato yield and reduce percolation below the root zone. Gencoglan et al. (2006) compared the response of green bean to subsurface drip irrigation and partial rootzone-drying irrigation. According to their results, the dry weight the green bean under subsurface drip irrigation was found slightly higher than that under partial rootzone-drying irrigation.

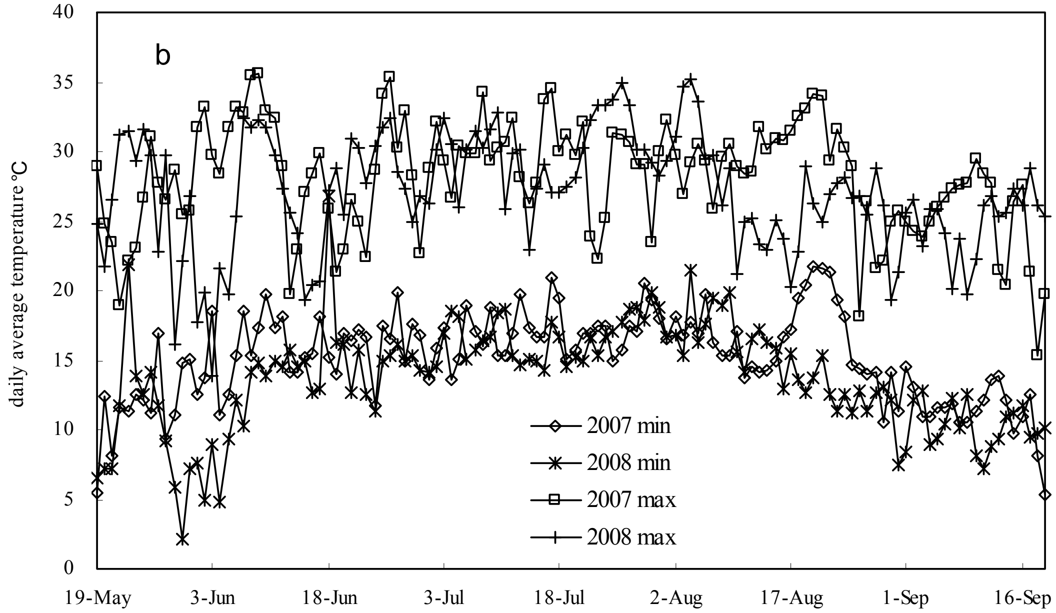
Therefore, the objective of this study was to compare the different influence of SDI and DI on bell pepper from the perspective of water content distribution, NO_3^--N distribution in soils, root distribution, crop yield and WUE, under different nitrogen fertilization levels.

2. Materials and methods

2.1. Location description

Field experiments were located at the Yuhe Irrigation Experiment Station, in Datong, Shanxi Province (40°06′ N; 113°20′ E; 1052m above sea level). The soil at the experimental sites is a gravelly loam, and the field capacity was 22.5%. The groundwater table is about 19m. The climate in Datong is semiarid, with average annual precipitation of approximately 379.3mm. Overall, most of the annual precipitation occurs during the growing season, which extends from late-May to mid-September. The frost-free period is about 110-130days. Weather data of the experimental site for 2 years 2007, 2008 are shown in Fig.1 .





(a) cumulative and daily average rainfall during the crop season; (b) daily average temperature

Fig.1 Weather data during the crop season

2.2. Experimental treatments and field preparation

The field experiment was conducted using a randomized complete block design with 9 treatments including two irrigation techniques (SDI, DI), four fertilization levels of 0, 75, 150, 300 kg nitrogen ·ha^{-1} (N_0, N_{75}, N_{150}, N_{300}) and a control treatment border irrigation (BI) (Table.1). Each treatment had three replications. The experiments were conducted during the crop growing seasons in 2007 and 2008.

Table 1 Nitrogen-fertilizer application rate during the growth period of bell pepper .

		Nitrogen application rate (kg N·ha^{-1})		
Irrigation method	treatment	blossom and fruit set period	the full bearing period	the late stages of development
SDI	SDI N_0	0	0	0

	SDI N_{75}	30	30	15
	SDI N_{150}	60	60	30
	SDI N_{300}	120	120	60
DI	DI N_0	0	0	0
	DI N_{75}	30	30	15
	DI N_{150}	60	60	30
	DI N_{300}	120	120	60
BI	BI	120	120	60

The field plot size was 15.0 m × 81.0 m. The field plot was divided into two equal sub-plots of 7.0 m × 81.0 m by a farming road (1 m in width). The plot with 7.0 m × 81.0 m size was divided into 27 equal plots of 7.0 m × 3.0 m.

The test crop was Tongfeng 16 , a local variety of bell paper. Two-month-old pepper seedlings were transplanted in the field with 40.0 cm in row spacing and 50.0 cm in plant spacing. The crop was irrigated with SDI or DI systems that were installed prior to planting in 2007. The laterals were installed between every other crop rows at space of 1.0 m, and the SDI laterals were buried at a depth of 20.0 cm between the two crop rows. Water was applied every 4 days using laterals (Netfaim super Taphoon 125) with 1.1 $L \cdot h^{-1}$ of drippers discharge at a spacing of 40.0 cm. A border irrigation treatment was also carried out in both in 2007 and 2008.

Soil water content was measured by a Time domain reflectometry (TDR). Three access tubes were placed at a depth of 1.0 m at a distance of 0, 25.0 and 50.0 cm from lateral pipe and water content (volumetric) was measured in all treatments (Fig.2). Total 48 PVC access tubes were installed. Soil water content at 0.0-20.0, 20.0-40.0, 40.0-60.0, 60.0-80.0 and 80.0-100.0 cm layers in root zone were measured before and after irrigation and after rainfall..

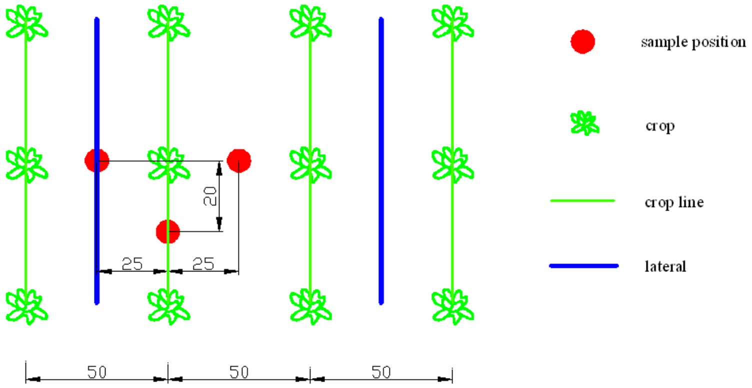


Fig.2 Layout for trime PVC tubes

2.3. Estimation of water requirement and irrigation application

The reference crop evapotranspiration (ET_0) was calculated by a Penman-Monteith's formula. The weather data were collected from an automatic weather station, 20 m away from the field site. The potential crop evapotranspiration was estimated by multiplying reference evapotranspiration with crop coefficient ($ET_C = ET_0 \times K_C$) at different crop growth stages. The adopted crop coefficients were recommended by FAO56. The total rainfall druing the crop growing season in 2007 and 2008 were 242.6 and 229.6 mm, respectively. Irrigation water requirement was calculated from the difference between ET_C and the effective rainfall. For the control treatment, the lowest water limit was set at 65-70% of field capacity and the designed moist layer was 40 cm. The applied water volume was monitored by a flow meter for each treatment. The crop was irrigated for 14 times in 2007. The irrigation amount was 257 mm for drip irrigation and 282 mm for border irrigation. However, the irrigation was reduced to 10 times in 2008 with 164 mm of the irrigation amount for drip irrigation and 165 mm for border irrigation.

2.4. Evapotranspiration estimation

The actual crop evapotranspiration was estimated using the following water balance equation:

$$ET_c = \Delta W + I + P - R - D \tag{1}$$

where ΔW is the change of soil water storage (mm); I is irrigation amount (mm); P is precipitation (mm); R is surface runoff (mm); D is the deep percolation (mm).

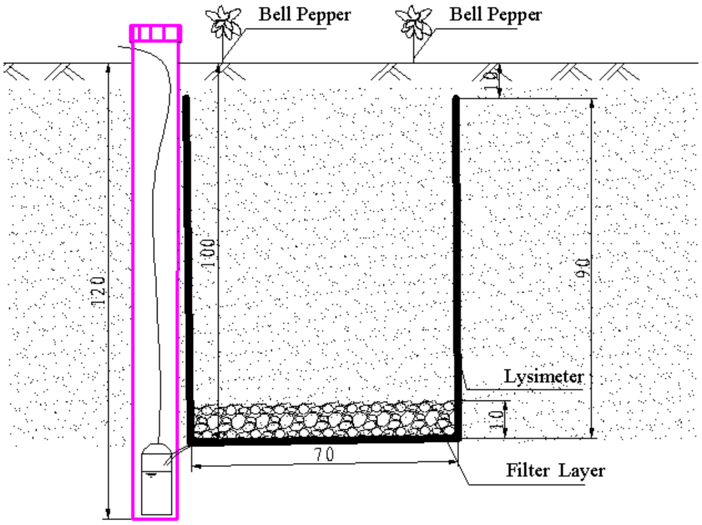


Fig.3 Structure of the simple lysimeter

ΔW was estimated using soil water content in the soil profile. Surface runoff was ignored throughout the stage. D is considered as water amount drained from a lysimeter (Fig.3 .).

2.5. Nutrient management

To meet the nutrition requirement of bell pepper, organic fertilizer (chicken manure: 11.1 m^3/hm^2) was homogeneously applied in all of the plots as basal fertilizer before land leveling. The contents of N, P(P_2O_5), K(K_2O) of organic fertilizer were about 1.63%, 1.54% and 0.085%. In addition, urea was applied as nitrogen fertilization that was supplied at different growth stages (Table.1).

Before and after fertilization, soil samples were collected from 0.0-20.0, 20.0-40.0, 40.0-60.0, 60.0-80.0 and 80.0-100.0 cm soil depths at 0.0, 25.0 and 50.0 cm distance from the lateral pipe. NO_3^--N content in soil water extract was calculated assuming that NO_3^--N was dissolved in the water. The extractable NH_4^+-N and NO_3^--N with 1 M KCl was performed by Flow Injection Analysis.

2.6. Yield

Bell pepper was manually harvested 4 times every year and its yield were determined by harvesting bell pepper at the physiological maturity in the two adjacent center rows in each plot. An analysis of variance was carried out by a SAS software package. Significant differences between means for different treatments were compared by means of the LSD test at $P < 0.05$.

2.7. Root sampling and analysis

Soil samples containing crop roots were taken in center rows after havest. The sampling area was 40.0 cm × 50.0 cm. Samples were taken at three different depths (0-10, 10-20 and 20-30 cm) in 2007, and four different depths (0-10, 10-20, 20-30 and 30-40 cm) in 2008. After washing away soils using a fine sieve, crop roots and organic debris were stored in plastic bags at 4℃ until further cleaning and then placed in a glass bowl. Crop roots were handpicked and placed in glass dishes. Root length density (RLD) and other root characteristic parameters were determined with Winrhizo (Re´gent Instrument Inc., Quebec City, Canada) software and hardware.

3. Results and discussion

3.1. Root distribution

Root system, the most active organ to absorb nutrients and moisture, is crucial for crop growth. Irrigation, fertilization and other agronomic practices affect the root growth, distribution and function and thereby affect crop production. The growth and development of crop root also influence the distribution and concentrations of water, nutrient and salt in soils.

Table 2 The percent of root length at different soil depths

	BI		DI N_{150}		SDI N_{150}	
Depth (cm)	root length (cm)	percentage (%)	root length (cm)	percentage (%)	root length (cm)	percentage (%)
0-10	4801	45.85	11582	66.26	15235	59.45
10-20	3731	35.64	4588	26.25	7353	28.69
20-30	1612	15.40	1089	6.23	2319	9.05
30-40	326	3.11	219	1.25	719	2.81
0-40	10470	100	17479	100	25625	100

As seen in Table 2, there was an obvious difference of root distribution between SDI and DI. The root length and its percentage decreased with soil depths. At 30-40 cm soil depth, the root percentage under BI, DI N_{150} and SDI N_{150} were as small as 3.11%, 1.25% and 2.81%, respectively. Below 40 cm soil depth, almost no root was observed. Drip irrigation, especially subsurface drip irrigation, can significantly promote the growth of roots. The total root lengths under SDI and DI were higher than that under BI by 2.44 and 1.67 times. Moreover, the root length under SDI was 1.46 times longer than that under DI. The percent of root length under SDI at 10 cm soil depth were higher than under DI by 7 percentage points, indicating that SDI not only promoted the root growth, but also result in deeper development of root.

The impact of different nitrogen amounts on RLD was showed in Fig.4. At 0-10 cm soil depth, RLD gradually increased with increasing nitrogen amounts. However, at 10-20 cm soil depth, RLD declined sharply when nitrogen amount was higher than 300 kg·ha^{-1}. The results implied that over nitrogen application would inhibit root growth into deeper soil layers.

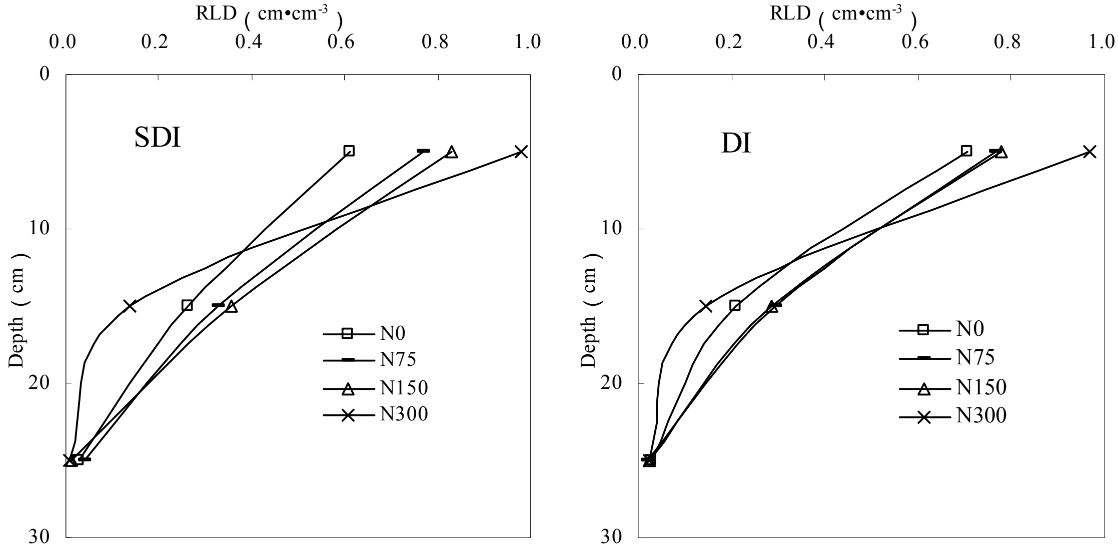


Fig.4 RLD distribution during the 2007 growing season in all treatment.

3.2. *NO_3^--N distribution in soils*

NO_3^--N concentrations at 0.0-20.0, 20.0-40.0, 40.0-60.0, 60.0-80.0 and 80.0-100.0 cm soil depths were determined for all treatments. Figure.5 shows NO_3^--N contents at 2 days before fertilization (14-Aug), 2 days after fertilization (18-Aug), and 22 days after fertilization (7-Sep) between different irrigation practices.

The impact of SDI and DI on NO_3^--N distribution in soil profile was compared under supplying 150 kg nitrogen ·ha^{-1}. Before fertilization, there was no significant difference of NO_3^--N distribution between SDI and DI. However, 2 days after fertilization, NO_3^--N concentration for SDI treatment appeared to be distributed with a parabolic curve with a maximum value (14.2 mg·kg^{-1}) at 20-40 cm soil depth. In the contrast, NO_3^--N concentration for DI treatment declined with the increase of soil depth and a maximum concentration (15.7 mg·kg^{-1}) was obtained at the top soil (0-20 cm). After fertilizing 22 days, NO_3^--N gradually moved downward with the water movement, crop growth and root activities.The maximum NO_3^--N concentration after 22 days fertilization for SDI and DI treatments occurred at 40-60 cm and 60-80 cm, respectively. NO_3^--N at deep soil (below 40-60 cm and 60-80 cm) were difficult to be utilized by bell pepper because of shallow root system, leading to NO_3^--N leaching. As mentioned above, SDI promoted the development of bell pepper roots and favored the establishment of intensive root layer, which can prevent nitrate leaching. The maximum residual NO_3^--N concentration at 40-60 cm for SDI treatment was 8.4 mg·kg^{-1} that was far less than that for DI treatment (13.8 mg·kg^{-1}, at 60-80 cm). At 300 kg N·ha^{-1} of nitrogen application amount, the residual NO_3^--N concentration for BI treatment was higher than that of all the drip irrigation treatments.

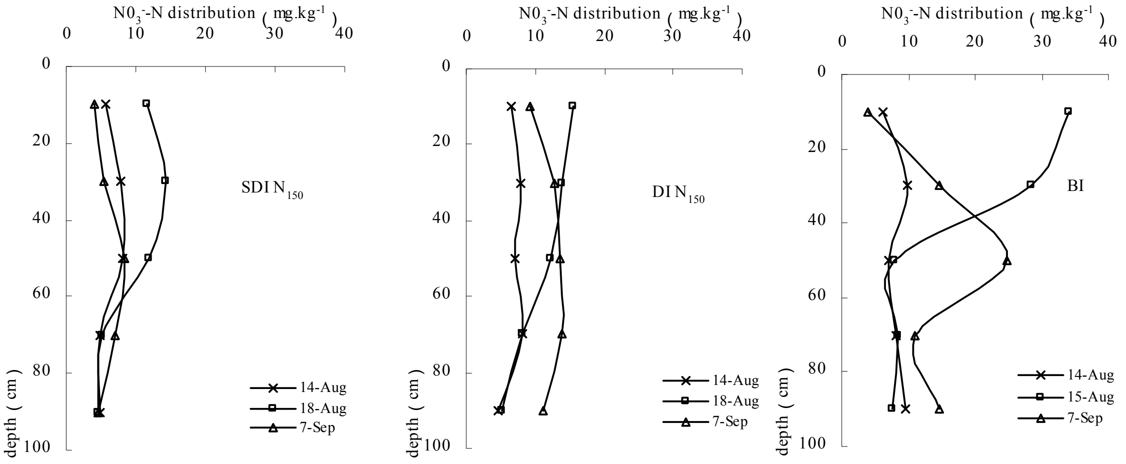


Fig.5 Vertical distribution of NO_3^--N centration in soil profiles.

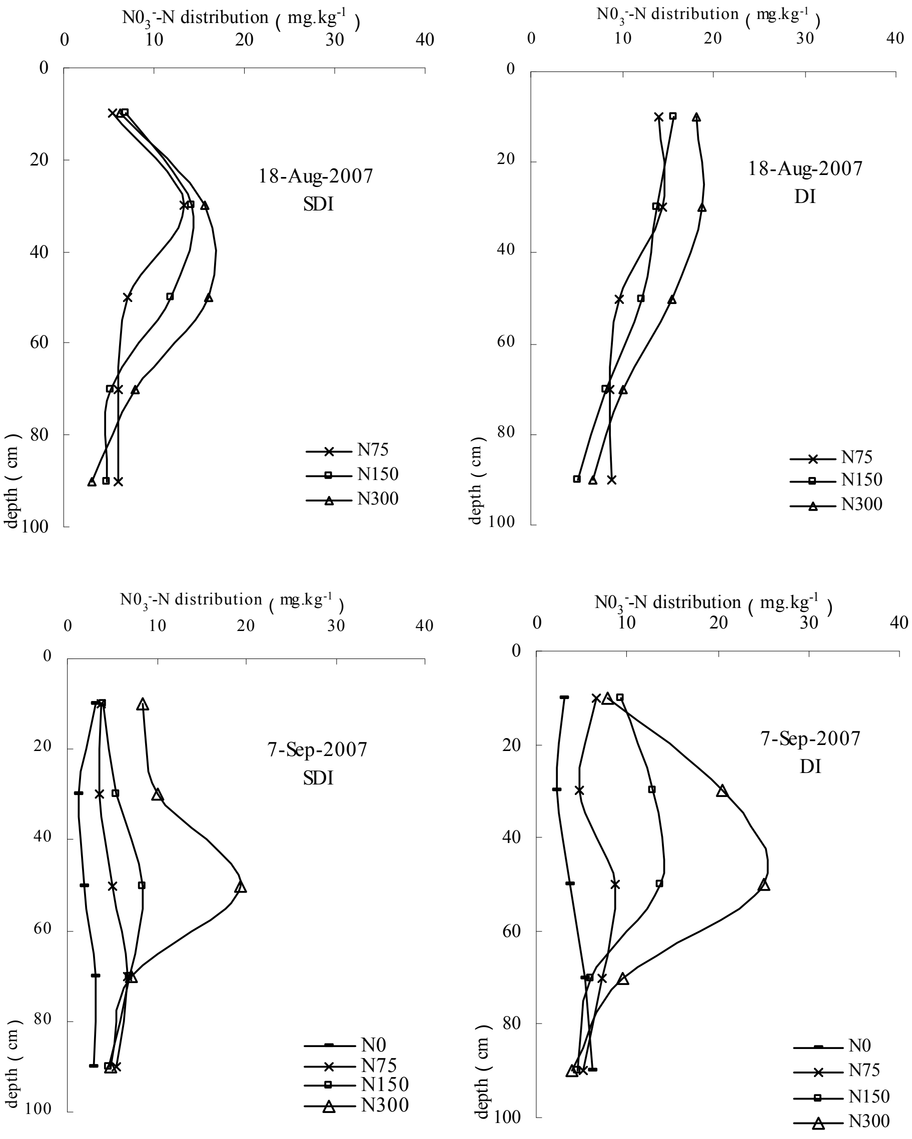


Fig.6 Vertical distribution of NO_3^--N as influenced by different nitrogen amounts.

In addition, the residual NO_3^--N concentration in soil profiles increased with increasing of the nitrogen fertilizer amount (Fig.6). This tend was found for all treatments of nitrogen amounts. In particular, NO_3^--N residual concentration for N_{300} treatment was significant higher than that for N_{150} treatment at 22 days after fertilization.

3.3. ET_C

Table.3 shows the cumulative water consumption of bell pepper during the two growing seasons. The monthly average temperature in 2008 were lower than that of 2007. Especially in 30-May-2008, a very low temperature (2.4 ℃) inhibited seedling establishment, which influence the bell pepper growth in all treatments of 2008.

In 2007, the maximum water consumption (451 mm) was found for DI N_{150} treatment and the minimum water (301 mm) consumption for SDI N_0 treatment. In 2008, the maximum value was 387 mm for DI N_{75} and the minimum value was 334 mm for SDI N_0.

Except for N_{300} treatment in 2007, all of the cumulative water consumptions under SDI were lower than under DI. For example, the water consumption for SDI N_0 treatment was lower than that for DI N_0 by 26% in 2007 and by 7% in 2008.

Table 3 The cumulative water consumption under different irrigation and fertilization practices.

	ET_0(mm)		ET_C(mm)			
			N_0	N_{75}	N_{150}	N_{300}
2007	508	DI	407	426	451	404
		SDI	301	405	438	432
		BI				451
2008	406	DI	362	387	382	382
		SDI	334	357	377	359
		BI				397

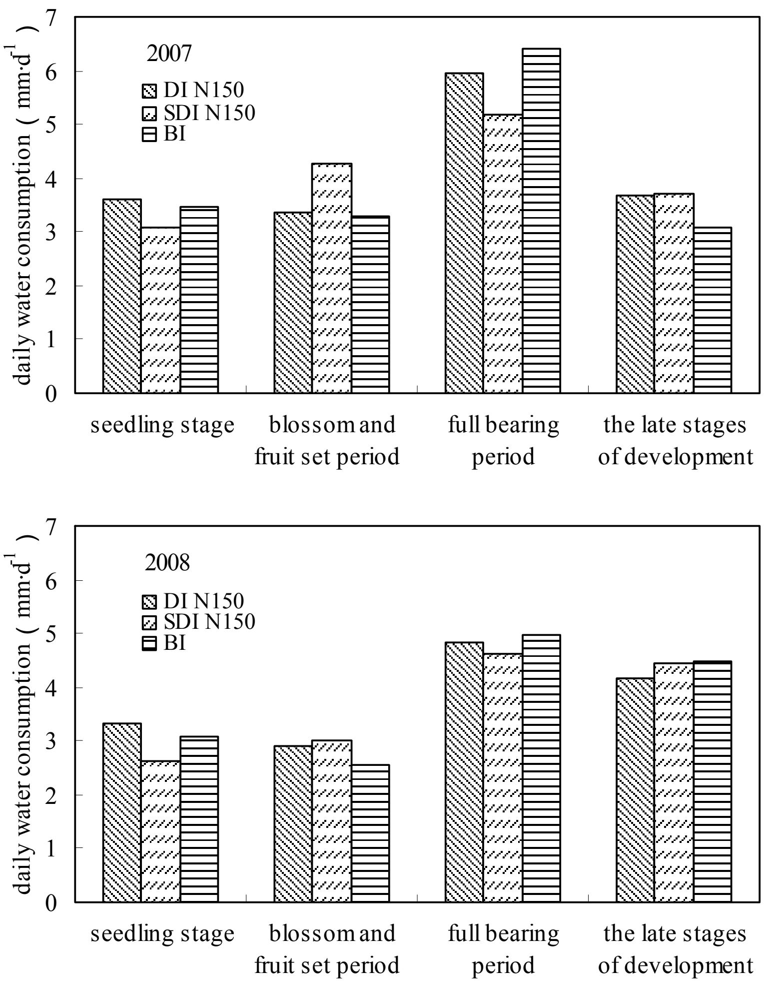


Fig. 7 Daily averaged water consumption at different growth stage

The daily averaged water consumption at different growth stage under different irrigation techniques was showed in Fig.7. At the period of seedling establishment, DI resulted in higher daily averaged water consumption than SDI. During this period, plants were small and evaporation accounted for most of evapotranspiration. Since SDI kept the surface soil dry, it decreased the evaporation, and thereby reduced the water consumption of bell pepper. After entering the blossom and fruit-set period, daily averaged water consumption under SDI was higher than that under DI. This result attributed to faster root growth under SDI than that under DI during the above main period of root growth. At the full bearing period, bell pepper grew vigorously and water consumption reached the maximum of the growth season. Water consumption under SDI were lower than that under DI and BI, which contributed to the low plant height and leaf area under SDI during the full bearing period. However, daily averaged water consumption under DI was slightly smaller than that under SDI in the late crop growth stages.

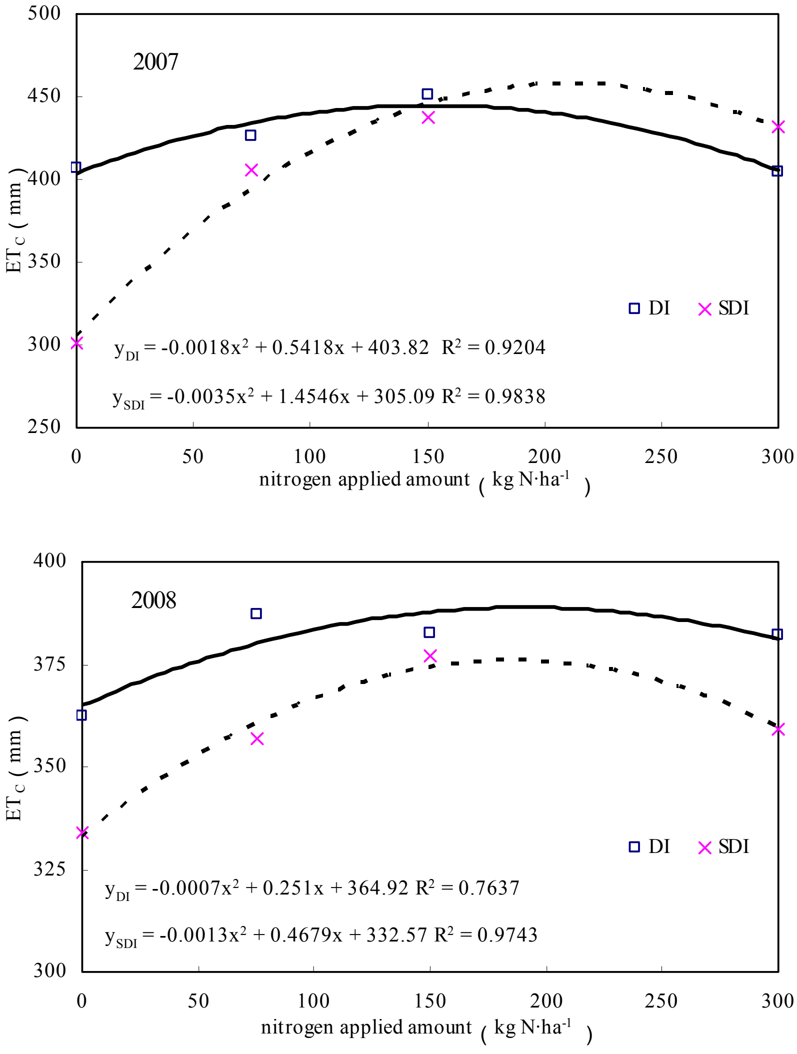


Fig.8 Relationship between ET_C and nitrogen amount

There was a significantly polynomial correlation between crop water consumption and nitrogen amount (Fig.8). The ET_C increased with increasing nitrogen amount and reached up to a maximum value at 150 kg nitrogen·ha^{-1}. Thereafter, ET_C declined again. The results revealed that nitrogen became excessive after 150 kg·ha^{-1}.

3.4. Yield and water use efficiency

During 2007-2008, bell pepper yields were measured for each treatment and shown in Table.4 .

Table 4 Bell pepper yield and WUE for different treatment.

year	treatment	SDI		DI		BI	
		yield (t•ha^{-1})	WUE (kg•m^{-3})	yield (t•ha^{-1})	WUE (kg•m^{-3})	yield (t•ha^{-1})	WUE (kg•m^{-3})
2007	N_0	39.46 c	13.11*	36.07 b	8.87		
	N_{75}	43.43 b	10.71	42.70 a	10.01		
	N_{150}	46.54*a	10.64	44.72*a	9.92		
	N_{300}	46.29 a	10.72	43.29 a	10.71*	31.88	7.07
2008	N_0	29.72 c	8.90	28.11 b	7.26		
	N_{75}	35.89 b	10.06	30.44 ab	7.86		
	N_{150}	42.83*a	11.35*	34.50*a	9.02*		
	N_{300}	35.44 b	9.87	30.17 ab	7.90	23.00	6.27

Values followed by different letters are significantly different at $p < 0.05$ using Duncan's test.

* indicate the highest yield and highest WUE.

Bell pepper yield under SDI was higher than that under DI by 4% in 2007, and by 13% in 2008. Furthermore, bell pepper yield under SDI and DI were significantly higher than that under BI. For instance, bell pepper yield under SDI were higher than BI by 32.4% in 2007 and by 51.1% in 2008. The maximum yield were obtained under SDI with supplying 150 kg·ha^{-1}(SDI N_{150}) SDI had a higher WUE than DI by 13% in 2007, and 21% in 2008.

Maximum WUEs were obtained under SDI without nitrogen supply (SDIN$_0$) in 2007 and under SDI with supplying 150 kg nitrogen·ha^{-1} (SDI N$_{150}$) in 2008.

Standard analysis of variance test were carried out with Duncan-test considered significant at the 0.05 level of probability. The result showed the fertilizer application amount had significant effect on bell pepper yield. The relationship between yield and fertilization nitrogen amount were conics, yield increased with urea fertilization up to a point (150-200 kg N·ha^{-1}) where fertilization became excessive.

There was a significantly polynomial correlation between bell pepper yield and cumulative water consumption (Fig.9). The result indicated that the bell pepper yield was improved when the water consumption increased in a certain range.

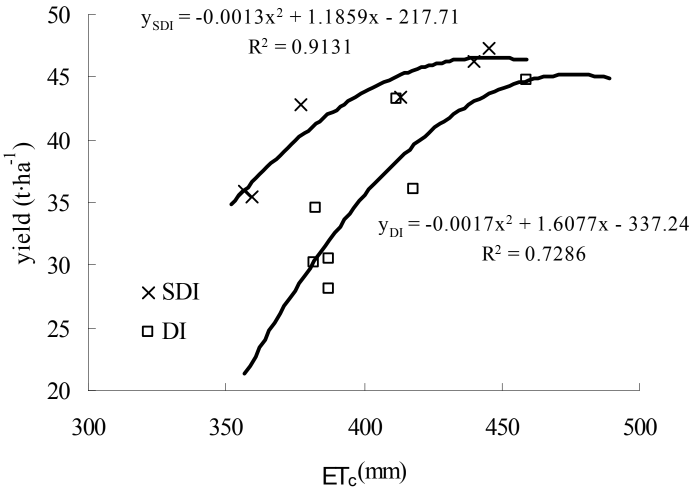


Fig.9 Relationship between yield and ET$_C$.

4. Conclusions

This study evaluated the different water consumption, soil water distribution, NO$_3^-$-N content, root distribution, bell pepper yield and WUE between SDI and DI.

The cumulative water consumption under SDI is lower than that under DI. SDI not only promoted the growth of root, but also resulted in the root development towards deeper soils. The distribution of NO_3^--N in soil profile is significantly influenced by nitrogen fertilizer amount. And as compared with DI, SDI is more favorable in nitrogen fertilizer utilization, which prevents nitrate leaching. Meanwhile, SDI can prevent high variations of water and nutrients in the soils and increase bell pepper yield.

The results suggests that SDI combined with N_{150} was recommended as the optimal irrigation and fertilization practices for improving bell pepper yield and WUE, reducing NO_3^--N leaching.

Acknowledgements

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The 2009 NRCS Irrigation Toolbox

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Abstract. *The original NRCS Irrigation Training Toolbox was created in 1997. It consisted of two large cardboard boxes that contained much of the best of the available irrigation documents, books and videos that existed at that time. The 2009 release of the renamed NRCS Irrigation Toolbox has updated many of the documents and added many more. The Irrigation Toolbox now includes a search engine, and is entirely electronic. The NRCS Irrigation Toolbox is delivered on DVD, SD drives and flash drives.*

Keywords. irrigation, toolbox, resource, video, PowerPoint, extension document, training.

Introduction

The original NRCS Irrigation Training Toolbox was developed in 1997 by a team of NRCS irrigation engineers; it consisted of a collection of the best irrigation information available at that time. The primary purpose of the toolbox was to assist NRCS employees to develop training sessions. It included books, VHS videotapes, and extension documents. It also included irrigation lesson plans that could be adopted as is, or modified for a particular state or area.

The source of the documents was varied. Many of the documents were produced by NRCS, but most of the information was produced by state extension offices and universities. The NRCS purchased about 100 copies of each item in the toolbox. Books, videos, and training course materials were organized into chapters and put into two cardboard boxes.

The Irrigation Training Toolbox was distributed to each NRCS state water management engineer in all 50 states. A number of states received more than one toolbox. Many partners of the NRCS also received a toolbox. Occasionally, as money for new items was obtained, the items were purchased and distributed.

Over the years, the contents were often removed from the boxes and scattered. As personnel changed, many forgot about the existence of the toolbox, and found other sources for irrigation related information and training materials. Additionally, much of the technology that was used in the toolbox became obsolete. This is not to say that the information necessarily became outdated, but that the delivery mechanism of the technology did. For example, the Irrigation Training Toolbox contained about 30 VHS video cassettes. Some of the original VHS videotapes were replaced by DVDs, but most remained in the toolbox as videotapes.

The 2009 NRCS Irrigation Toolbox

Recently, water management engineers at Natural Resources Conservation Service decided that the original Irrigation Training Toolbox needed updating. The technology advancements in the past 12 years made it possible to make the toolbox even more functional than ever. Specifically, digitizing the contents of the toolbox allow effective searches to be conducted. The videos were reformatted so that they can be played on desktop or laptop computers. Additional information was included so that the irrigation technology is up-to-date.

The size of the Toolbox has been limited to 3.75 Gigabytes so that it can be delivered on a standard DVD. In addition, other copies of the Toolbox are delivered on SD cards and flash drives.

In the future, the Toolbox will be updated on an online site where NRCS employees can download the entire toolbox and copy it to their preferred storage device. The current storage limit of 3.75 GB will certainly be increased as the cost of storage continues its decline.

Contents

The NRCS Irrigation Toolbox contents have been placed in a web-like format. The user accesses the contents through a set of html pages. Most content is in pdf format.

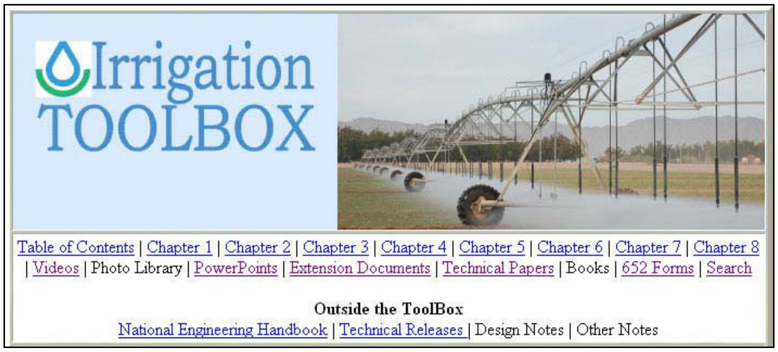


Figure1. The NRCS Irrigation Toolbox “Header”

Videos

The most pressing issue for the 1997 version of the Toolbox was the increasingly obsolete VHS format of the excellent videos. Finding a VCR player in NRCS field offices is increasingly difficult. The existing videos were re-formatted in flash, and can be viewed within the user's internet browser. The flash format also allows the 30 hours of video in the Toolbox to be placed on one DVD.

Search Engine

Another significant advantage of the electronic version of the Toolbox is the ability to do a search. It is typical that people forget about the resources in their own office. In the age of Google, finding information has becoming vastly simpler, but that implies that the information is already digitized and indexed.

Zoom Search Engine 5.1, a third party search engine, was purchased and installed, so that all of the documents can be found using the search page. The documents were indexed with the Zoom search engine, and the index files added to the Toolbox. The search engine can index many types of files, and returns both the file's title and description, and also the context of the word "hit".

The search engine uses an algorithm to determine the document's score, and the documents with the highest score are placed first. A high score represents the fact the search words occur frequently, and extra weight is given if a search word occurs in the document title.

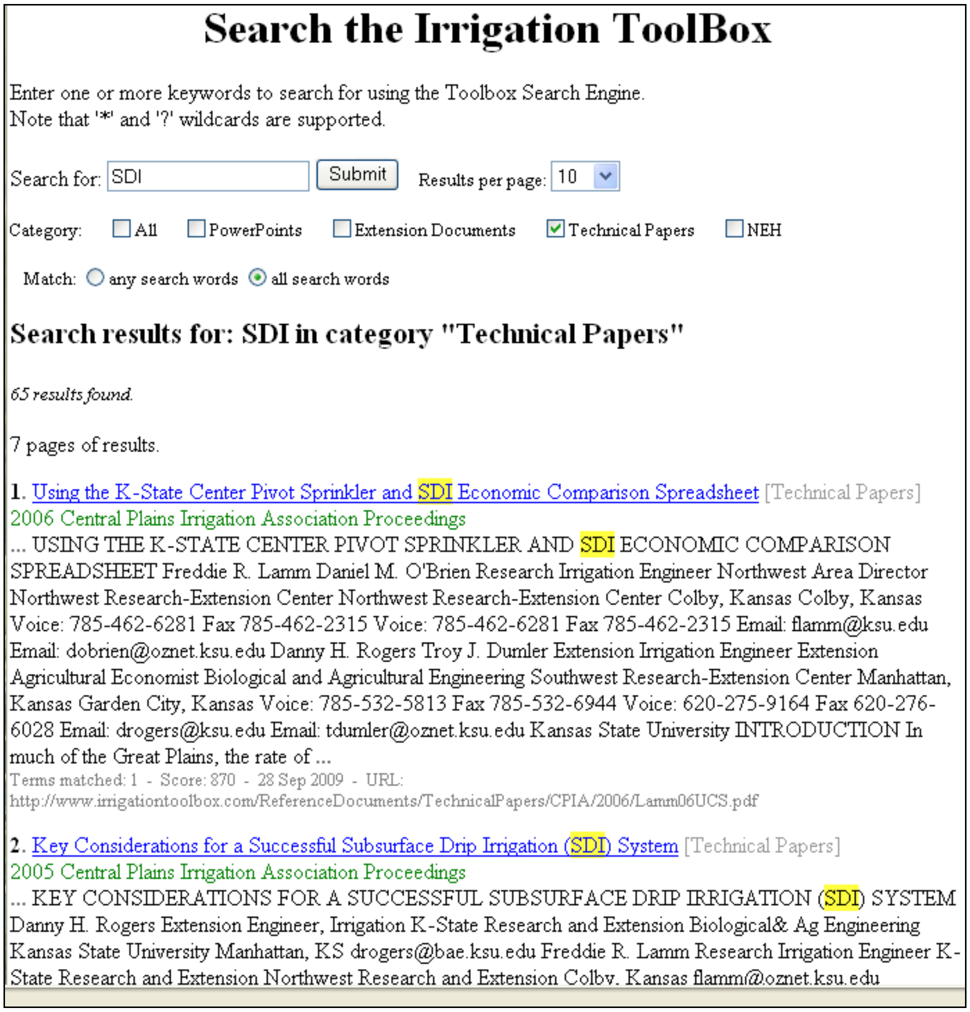
The search page allows the user several options. For example, the user can choose to search only specific sections of the Toolbox. These sections include:

- Technical Papers
- Power Points
- Extension Documents
- NRCS National Engineering Handbook

In addition, the user can search the entire contents of the toolbox. Conventions typical for most search engines are used in the Toolbox. For example, quotes indicate that the exact phrase must be found.

The Zoom search engine can be configured so that it works while installed on external drives like DVDs, SD cards, and flash drives. The Irrigation Toolbox is fully functional without an internet connection, and in the case of an SD card or DVD, can remain inside a laptop.

Searching the large amount of NRCS produced irrigation information, extension documents, and technical papers from the Irrigation Association and Central Plains Irrigation Association allows NRCS employees to find answers to very specific irrigation questions. It also introduces the employee to new sources of information.



Search the Irrigation ToolBox

Enter one or more keywords to search for using the Toolbox Search Engine.
Note that '*' and '?' wildcards are supported.

Search for: SDI

Results per page: 10

Category: ☐ All ☐ PowerPoints ☐ Extension Documents ☑ Technical Papers ☐ NEH

Match: ○ any search words ● all search words

Search results for: SDI in category "Technical Papers"

65 results found.

7 pages of results.

1. Using the K-State Center Pivot Sprinkler and SDI Economic Comparison Spreadsheet [Technical Papers]
2006 Central Plains Irrigation Association Proceedings
... USING THE K-STATE CENTER PIVOT SPRINKLER AND SDI ECONOMIC COMPARISON SPREADSHEET Freddie R. Lamm Daniel M. O'Brien Research Irrigation Engineer Northwest Area Director Northwest Research-Extension Center Northwest Research-Extension Center Colby, Kansas Colby, Kansas Voice: 785-462-6281 Fax 785-462-2315 Voice: 785-462-6281 Fax 785-462-2315 Email: flamm@ksu.edu Email: dobrien@oznet.ksu.edu Danny H. Rogers Troy J. Dumler Extension Irrigation Engineer Extension Agricultural Economist Biological and Agricultural Engineering Southwest Research-Extension Center Manhattan, Kansas Garden City, Kansas Voice: 785-532-5813 Fax 785-532-6944 Voice: 620-275-9164 Fax 620-276-6028 Email: drogers@ksu.edu Email: tdumler@oznet.ksu.edu Kansas State University INTRODUCTION In much of the Great Plains, the rate of ...
Terms matched: 1 - Score: 870 - 28 Sep 2009 - URL: http://www.irrigationtoolbox.com/ReferenceDocuments/TechnicalPapers/CPIA/2006/Lamm06UCS.pdf

2. Key Considerations for a Successful Subsurface Drip Irrigation (SDI) System [Technical Papers]
2005 Central Plains Irrigation Association Proceedings
... KEY CONSIDERATIONS FOR A SUCCESSFUL SUBSURFACE DRIP IRRIGATION (SDI) SYSTEM Danny H. Rogers Extension Engineer, Irrigation K-State Research and Extension Biological& Ag Engineering Kansas State University Manhattan, KS drogers@bae.ksu.edu Freddie R. Lamm Research Irrigation Engineer K-State Research and Extension Northwest Research and Extension Colby, Kansas flamm@oznet.ksu.edu

Figure 2. The NRCS Irrigation Toolbox “Search Page”

Technical Papers

The Irrigation Association and the Central Plains Irrigation Association generously granted the NRCS Irrigation Toolbox the electronic rights to their technical papers. These papers contain a wealth of information including research, application, and experience in the field of irrigation. Importantly, the Toolbox allows the user to search only these technical papers, excluding the rest of the toolbox, so that the user can find information that is specifically included in any technical paper.

Extension Documents

The Toolbox also includes many of the best of the extension documents that are available online. These extension documents have been developed by the various state extension offices. In most cases, these documents were indexed using the version downloaded from its host site. In some cases, however, the extension document was security protected so that indexing was not allowed. In these cases, a printout of the extension document was scanned, and that new document was indexed. This requires that the new, copied document be placed temporarily in the Toolbox. After indexing, the original, security protected document was then put back in the Toolbox so that the user can access only the original, security protected document.

Photo Library

The Irrigation Toolbox includes over 400 high quality digital photographs taken by NRCS employees. The photos are included so that custom PowerPoint slide shows can be developed. Additionally, the photos are often educational in their own right. They include photos taken at site visits around the country, and show the variety of irrigation systems found in the United States. The slides include many of the various permutations of center pivot and micro irrigation systems. Additionally, it includes a set of photographs of irrigation related appurtenances.

Figure 3. Page from the NRCS Irrigation Toolbox Photo Library

PowerPoint Slideshows

Over the years, many NRCS irrigation engineers have developed PowerPoint sideshows for training. The Irrigation Toolbox has a total of 55 irrigation related Power Points sideshows. The subject matter ranges from irrigation scheduling to developing a water management plan. The intent is to allow other NRCS employees to either use or modify these existing PowerPoint presentations.

Lesson Plans

The original toolbox was designed to be used by trainers as they developed local training sessions for NRCS employees. The original lesson plans have been updated and organized into chapters. The chapter subjects are:

1. Soil-Water-Plant Relationship
2. Irrigation System Planning
3. Irrigation System Design
4. Water Measurement
5. Irrigation Scheduling
6. Soil Moisture Measurement
7. Irrigation Water Management
8. Irrigation System Evaluation

Accessing the Information

The Irrigation Toolbox is designed to allow the user to find information easily. Much of the information is listed on two different pages: the subject (chapter) page and the "Type of Information" page. For example, an extension document on using tensiometers for irrigation scheduling would be listed in the chapter on Irrigation Scheduling, and also in the Extension Document page. Finally, the document could be found by using the search engine.

Conclusion

The Natural Resources Conservation Service (NRCS) is the lead agency of the United States Department of Agriculture charged with carrying out the Department's conservation mission on private lands. Assisting landowners with irrigation will continue to be a major focus of the agency in the future. The ability to access accurate information on irrigation is critical to NRCS employees at all levels. The 2009 NRCS Irrigation Toolbox is a product that the agency believes will fill the need of employees for high quality irrigation information and training materials.

Acknowledgements

The NRCS wants to acknowledge all those organizations and individuals that consented to have material they developed included in the NRCS Irrigation Toolbox. Also, NRCS water management engineers who worked on the Toolbox but are not listed as authors of this paper include Ronald Gronwald, Tony Stevenson, and Jerry Walker.

Tools an NRCS Field Office Could Use to Help an Irrigator

By: Jon Whan, Zone Civil Engineer, USDA – NRCS Corpus Christi, Texas

Introduction

There are several models that engineers and conservation planners can use to help landowners make decisions on irrigation systems. In this paper I will cover the basic ones user in the Edwards Aquifer Area of South Central Texas.

Background:

The Edwards Aquifer is one of the major groundwater systems in Texas. Today, it is the primary source of water for approximately 1.7 million people. The Edwards Aquifer is one of the world's unique groundwater resources, extending 180 miles from Brackettville in Kinney County to Kyle in Hays County, Texas. Water in the aquifer is used for household, agricultural, industrial and recreational purposes.

For years, it was thought the Edwards Aquifer was a never-ending supply of fresh drinkable water. In the 1950s, a seven-year drought drastically lowered water levels in the aquifer. In the 1980s and 1990s, droughts of shorter duration occurred, and required heavy pumping from wells. Average pumping from Edwards's wells has increased dramatically in the last five decades because of population growth and demand.

In 1940, the region was pumping 120,000 acre-feet of water, or 39 billion gallons, a year. In 1989, regional pumping reached a maximum of 542,000 acre-feet of water per year - more than 175 billion gallons.

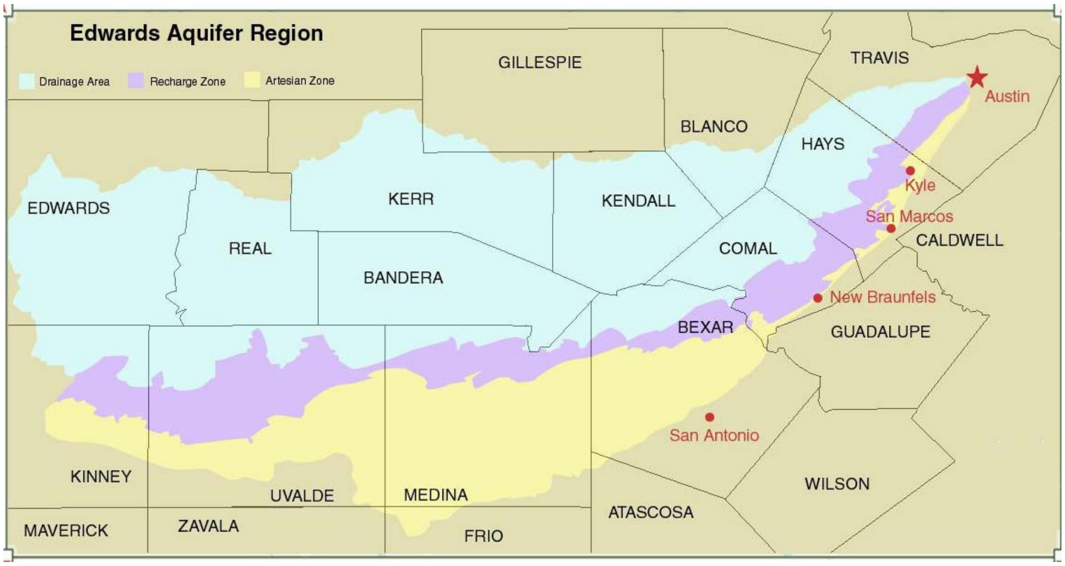


Figure 1 – Edwards Aquifer Region

The Edwards Aquifer Authority Act was passed in 1993. However, legal challenges prevented the implementation of the Act until June 1996. One of the policies that were enacted was to limit irrigated agricultural farm land to a 2 acre/feet per acre of water allotment.

Models:

With the water limitations that have been imposed on the farmers in the area, the need for good water management decisions has also increased. The use of modeling software to help farmers make these decisions is one way of showing the differences in the water application and absorption for various crops and soil types. The Natural Resources Conservation Service (NRCS) in Texas placed a six person team in the Edwards aquifer area to assist farmers in advancing to more efficient irrigation systems. The team is using several irrigation models to help the farmer see what their current system on a field is doing and how a change to a different system might affect their water use.

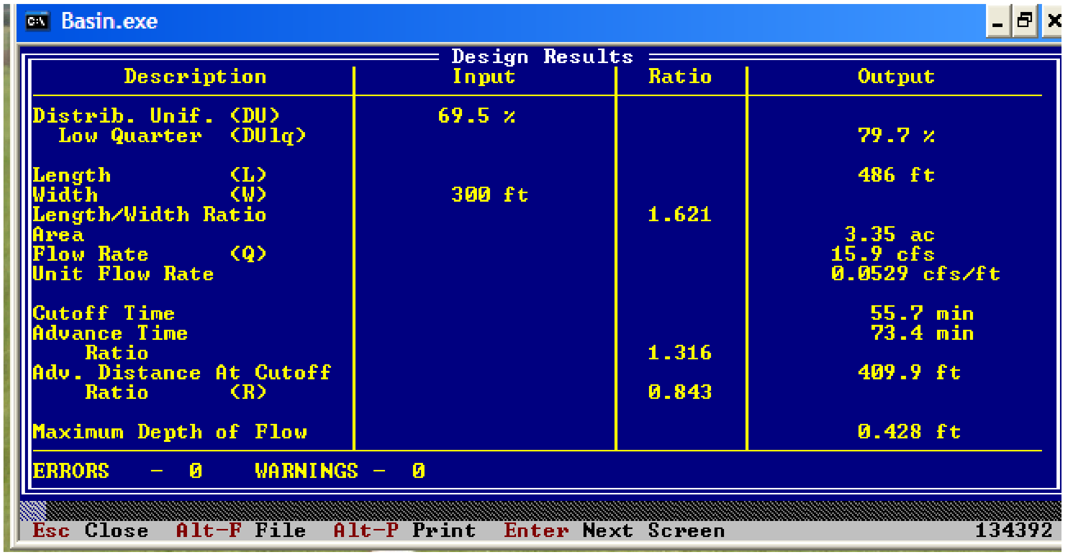
The Field:

One of the most important pieces of information NRCS can give the farmer is information on his field. One of the first steps and services NRCS can provide for the farmer, seeking ways to improve irrigation efficiency is a topo survey of the field. With this survey NRCS can look at things like: length of run, slope of field, maximum size of system, size of field, etc. This step can be done in any of the Civil Engineering software packages that are on the market or by hand. In the Hondo area NRCS is using an off the shelf civil engineering package called Eagle Point[1] to create our contour maps. NRCS also has the Survey Engineering Tool (SET)[2] to do this task.

Figure 2 – Typical Topo Survey Map

Surface Irrigation:

Since most of the existing systems in the area are flood irrigation, the team needs a good way to estimate and model the existing system. The software models that for NRCS approved use are the USDA – Agricultural Research Service (ARS) surface irrigation software developed at the Phoenix, Arizona Water Conservation Laboratory. These models include SRFR[3], BORDER[4], and BASIN[5].



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                                Design Results
       Description              Input          Ratio           Output
Distrib. Unif. (DU)            69.5 %
  Low Quarter  (DUlq)                                          79.7 %

Length         (L)                                             486 ft
Width          (W)              300 ft
Length/Width Ratio                             1.621
Area                                                          3.35 ac
Flow Rate      (Q)                                           15.9 cfs
Unit Flow Rate                                               0.0529 cfs/ft

Cutoff Time                                                     55.7 min
Advance Time                                                    73.4 min
    Ratio                                      1.316
Adv. Distance At Cutoff                                        409.9 ft
    Ratio      (R)                             0.843

Maximum Depth of Flow                                          0.428 ft
ERRORS   -  0    WARNINGS -  0

Esc Close  Alt-F File  Alt-P Print  Enter Next Screen                  134392
```

Figure 4 – Output from WinSRFR

SRFR is the model used the most. It is a one dimensional mathematical model that simulates surface irrigation. It can model borders, basins or furrows. The main variable that can be changed is the length of run for the type of system being modeled. When modeling a furrow system the software can only work on a single furrow. The team will determine an average furrow length and slope to run in the software. The output that is the most useful to the team on dealing with farmer and landowner is the irrigation efficiency and the depth of application. BORDER and BASIN are specialized models to handle flood irrigation of either borders or basins. The same information can be obtained from these models to show the farmer how their system is operating and possible improvements. Some of the suggestions that can be shown with these models are: changing slope of run, length of run or surge irrigation, just to name a few.

Now ARS has combined the three software packages into a windows version. The new version is called WinSRFR[9]. It is a hydraulic analysis application that combines a simulation engine with tools for irrigation system evaluation, design, and operational analysis.

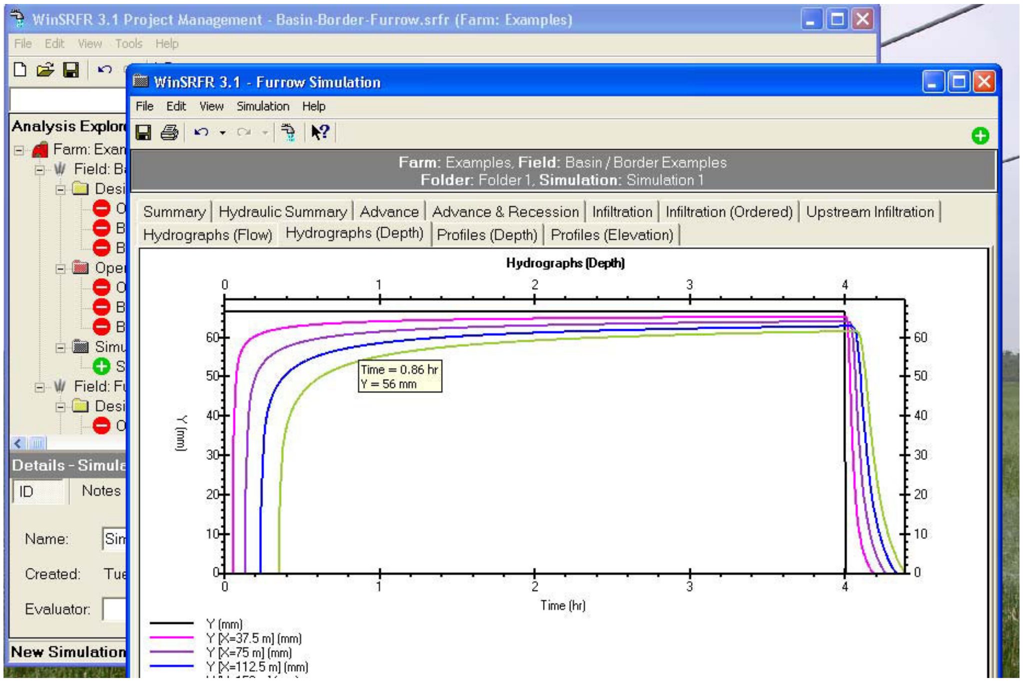
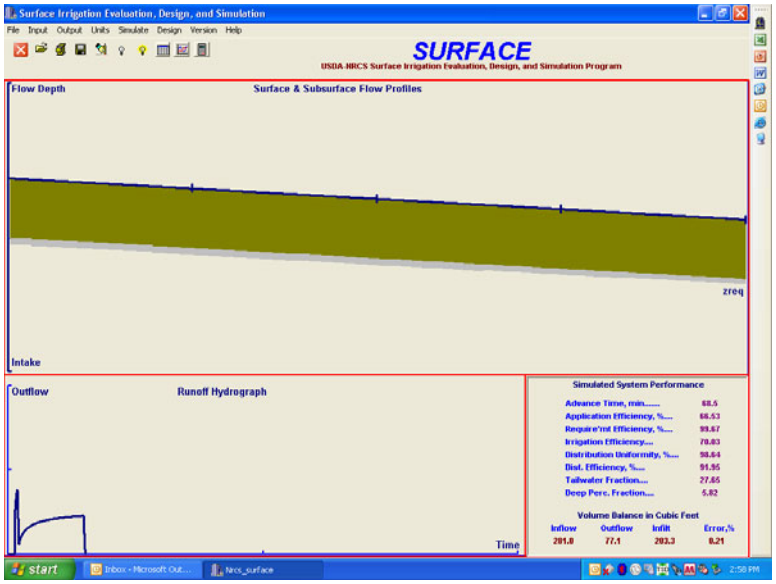


Figure 5 – Output from WinSRFR

Also, NRCS has developed a new surface irrigation model called SURFACE[10] . Surface takes inputs such as inflows, field topography, geometry of channel, infiltration characteristics and Hydrographic inputs. The hydrographic inputs include such things as an inflow hydrograph, tail water or runoff hydrograph, and advance and recession data.

Some of the outputs the program can give you to help you make decisions on the type of system being modeled include advance time, application efficiency, irrigation efficiency, distribution uniformity, and volume balance including inflow, outflow and infiltration.



```
Simulated System Performance

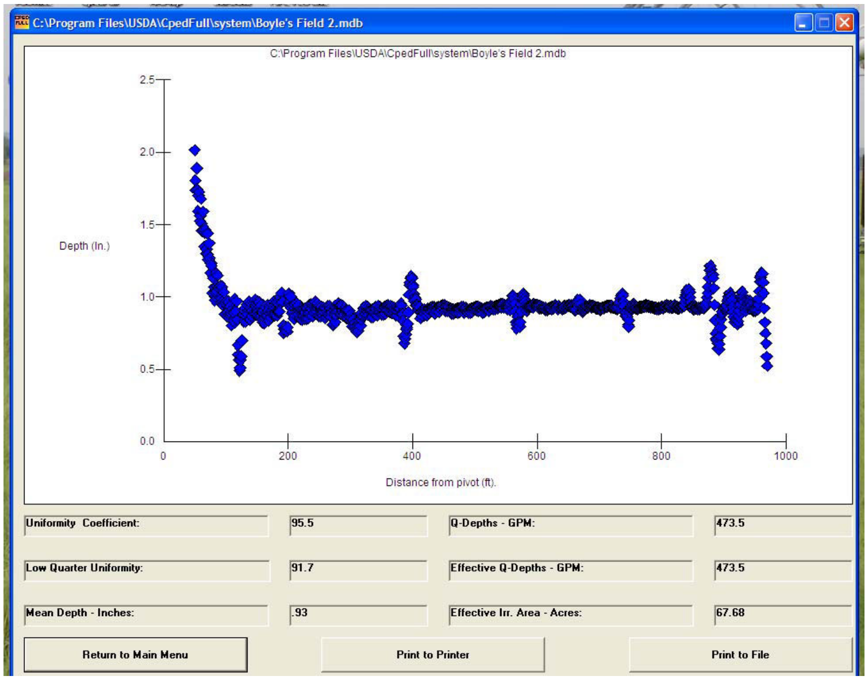
Advance Time, min......          68.5
Application Efficiency, %....    66.53
Require'mt Efficiency, %....     99.67
Irrigation Efficiency....        70.03
Distribution Uniformity, %....   98.64
Dist. Efficiency, %....          91.95
Tailwater Fraction....           27.65
Deep Perc. Fraction....          5.82

Volume Balance in Cubic Feet
Inflow     Outflow     Infilt     Error,%
281.0      77.1        203.3      0.21
```

Figure 6 – Output from SURFACE SOFTWARE

Sprinkler Irrigation:

Most of the farmers and landowners in the area want to upgrade to sprinkler irrigation systems. In this particular area NRCS is promoting low pressure systems with the nozzles close to the ground. ARS has a computer program called Center Pivot Evaluation and Design (CPED)[6] Software. With this software the proposed nozzle package can be modeled. The software will model a catch can test and report results like CU and DU. These can be used to compare the different systems.



Uniformity Coefficient: 95.5

Low Quarter Uniformity: 91.7

Mean Depth - Inches: .93

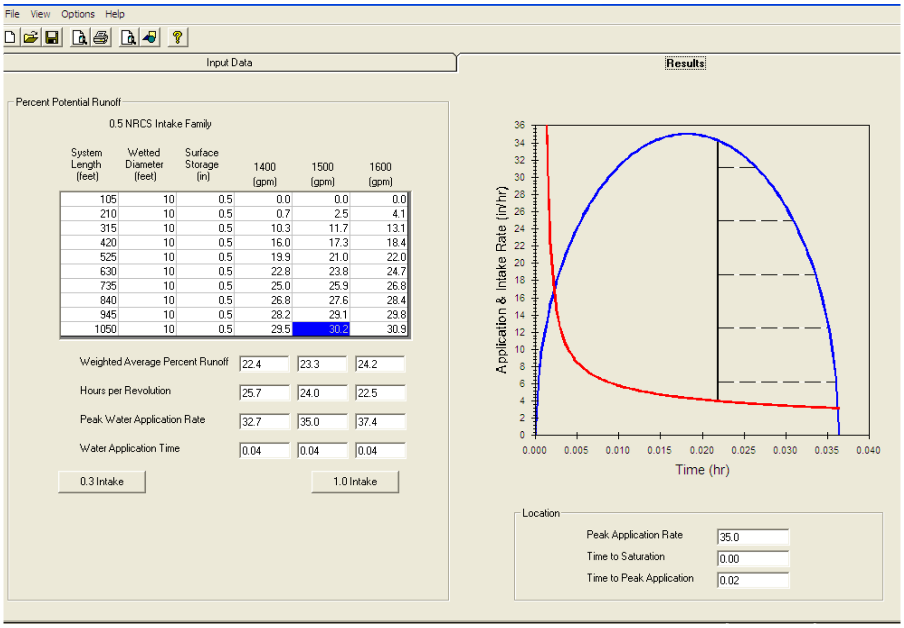
Q-Depths - GPM: 473.5

Effective Q-Depths - GPM: 473.5

Effective Irr. Area - Acres: 67.68

Figure 7 – Typical Output from CPED

Once the sprinkler nozzle package has been checked in CPED, the next step is to review using the software CPNOZZLE[7]. This software was developed in Nebraska, and is used to estimate the amount of runoff that would be expected from the pivot system given the type of soil and the amount of residue cover in the field. This is a good tool used to assist the producer in making irrigation water management decisions. If the model is showing high runoff, different tillage or surface storage options are analyzed and recommended to control the issue.



Percent Potential Runoff

0.5 NRCS Intake Family

System Length (feet)	Wetted Diameter (feet)	Surface Storage (in)	1400 (gpm)	1500 (gpm)	1600 (gpm)
105	10	0.5	0.0	0.0	0.0
210	10	0.5	0.7	2.5	4.1
315	10	0.5	10.3	11.7	13.1
420	10	0.5	16.0	17.3	18.4
525	10	0.5	19.9	21.0	22.0
630	10	0.5	22.8	23.8	24.7
735	10	0.5	25.0	25.9	26.8
840	10	0.5	26.8	27.6	28.4
945	10	0.5	28.2	29.1	29.8
1050	10	0.5	29.5	30.2	30.9

Weighted Average Percent Runoff	22.4	23.3	24.2
Hours per Revolution	25.7	24.0	22.5
Peak Water Application Rate	32.7	35.0	37.4
Water Application Time	0.04	0.04	0.04

Location

Peak Application Rate 35.0

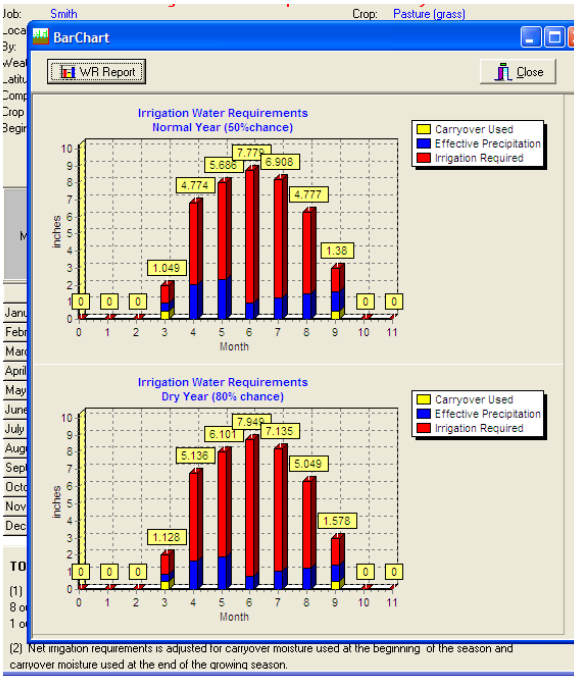
Time to Saturation 0.00

Time to Peak Application 0.02

Figure 8 – Typical CPNozzle Runoff Output

Irrigation Water Management:

One of the last models NRCS will use and discuss with the landowner is Irrigation Water Requirements (IWR)[8]. This model provides an estimate of irrigation water needed by analyzing consumptive use. The software can be customized for an area by loading local weather and crop data. Some of the output information includes: Monthly estimate on net irrigation requirements for a normal and dry year, Typical ET monthly estimate, Monthly Crop ET, Graph showing water use monthly, and ET curves. The outputs can be used to help explain the water requirements of the crop to the landowner or farmer.



(2) Net irrigation requirements is adjusted for carryover moisture used at the beginning of the season and carryover moisture used at the end of the growing season.

Figure 9 – Typical output from IWR on crop water use

Summary:

In closing, at present there is not just one model that can cover all the issues that water management planners might encounter. There are several new models available and some of the ones currently being used have been updated. Any model that helps get the point across to the landowner can be useful to an office as a planning tool. The main issues associated with the use of any of these models are whether they are being used appropriately and whether the output provides an easy to use and effective tool top explain recommendations to the landowner.

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[10] NRCS, SURFACE [Computer Software].

Variable-Rate Irrigation Management for Peanut in the Eastern Coastal Plains

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Variable rate irrigation systems provide a tool to spatially allocate limited water resources while potentially increasing profits. The reasons for spatial water application were local site-specific problems that included the following: spatial variability in topography, soil type, soil water availability, landscape features, cropping systems, and more recently water conservation. Although technology for spatial water application is available and it has high grower interest, farmers that have retrofitted their center pivot systems to be able to make precision applications are basing the application rates on their past experience and knowledge of variability in their fields. Science-based information is needed on how to precision-apply water with these systems. Sadler et al. (2005) identified critical needs for site-specific irrigation research that included decision support systems for spatial water application and improved real time monitoring of field conditions with feedback to irrigation systems.

Some researchers are working with growers to use soil electrical conductivity (EC) maps of fields together with historic yield maps to develop management zones (Lund, et al. 2001). Soil EC measurements in non-saline soils are driven primarily by soil texture and soil moisture. Those same factors correlate highly to the soil's water-holding capacity. Thus, an EC map can serve as a proxy for soil water-holding capacity, resulting in soil EC and yield maps that frequently exhibit similar spatial patterns. A few researchers are developing wireless communication systems to provide feedback to irrigation system controllers and for remote real time monitoring of soil and plant conditions (Kim and Evans, 2005, and Vellidis et al., 2005). In fields that are highly variable many sensors would be required to provide useful site-specific soil water monitoring. This can be very expensive.

Another approach to site-specific management would be using decision support systems to assist with spatial irrigation application. Currently there are no readily identified decision support systems for site-specific water management. However, the USDA-ARS National Peanut Laboratory in Dawson, Georgia has developed and distributed an expert system for peanut management (Irrigation Pro). Irrigator Pro assists producers with irrigation management by integrating several factors including soil type, yield potential, previous crop, cultivar, and planting date. During the growing season, the expert system requires inputs of rainfall, soil temperature, percent chance of rain, canopy size, and date of fruit initiation, among others, to recommend a decision on when and how much to irrigate. Irrigator Pro has typically been used for uniform (whole field) applications. In this research we will evaluate the potential of using Irrigator Pro to spatially manage irrigation under a site-specific variable rate irrigation system. Our specific objective will be to compare spatial irrigation management using both Irrigator Pro and traditional soil water potential measurements.

Methods

Experiments were conducted under the variable rate irrigation system located at the USDA-ARS Coastal Plains Soil, Water, and Plant Research Center in Florence, South Carolina. The system was developed in 1995 and consisted of a center pivot irrigation system that had been modified to permit variable applications to individual areas 9.1 by 9.1m in size (Omary et al., 1997; Camp et al., 1998). The center pivot length was divided into 13 segments, each 9.1 m in length. Variable-rate water applications were accomplished by using three manifolds in each segment, each with nozzles sized to deliver 1x, 2x, or 4x of a base application depth at that location along the center pivot length. All combinations of the three manifolds provided application depths of 0 through 7x of the base rate. When the outer tower was operated at 50% duty cycle, the 7x depth was 12.7 mm. The variable-rate water delivery system solenoid valves were controlled by a computer and programmable logic controller (PLC) that obtained positional (angular) data from the C:A:M:S management system (Valmont Industries, Inc., Valley, Neb.). A program written in Visual Basic controlled the PLC with user-supplied positional data, and angular position from the center pivot management system. A more detailed description of the water delivery system may be found in Omary et al. (1997) and, of the control system in Camp et al. (1998).

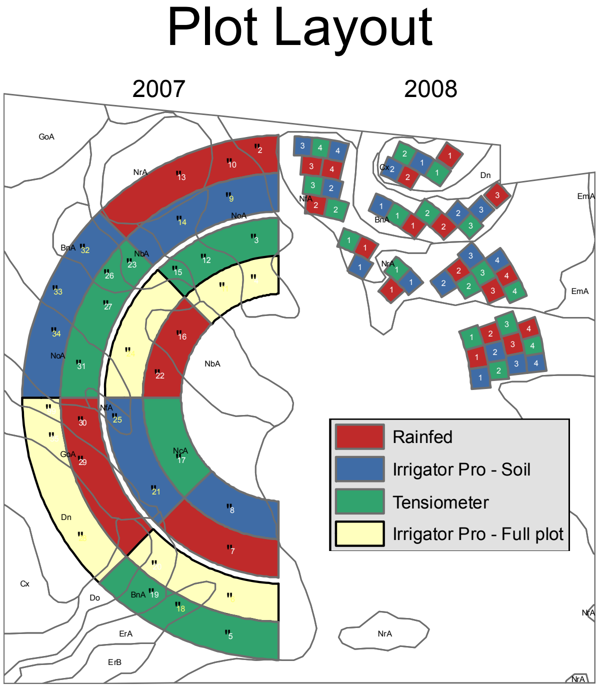

Figure 1. Plot layout for irrigated and non-irrigated treatments for 2007 and 2008.

Irrigation experiments were conducted using peanut to evaluate three spatial irrigation scheduling methods (Figure 1). Peanuts (variety NC-V11) were planted in May of 2007 and 2008 under one half (~3 ha) of the variable rate irrigation system. Soils under the center pivot system are highly variable and have been extensively spatially monitored with various field crops since the mid 1980's. Four irrigation treatments were used in the study: 1) using Irrigator Pro to spatially manage irrigation based on the predominate soil in a management zone; 2) using Irrigator Pro to spatially manage irrigation based on individual soils in a management zone; 3) using soil water potential measurements in management zones to maintain acceptable soil water potentials (<30 kPa) in the surface 30 cm of each soil; and 4) a non-irrigated treatment. Figure 1 details the plot layout for both 2007 and 2008.

The peanut crop was managed for planting, tillage, and disease and pest control using Clemson University Extension recommendations for profitable peanut production (http://virtual.clemson.edu/groups/peanuts/mmaker06.PDF , Chapin et al., 2006).

Results

Peanut yields among the treatments differed for the two years of the study (Table 1). The yield differences in 2007 were mainly attributed to the weather conditions that saw an extended drought condition for the latter part of the growing season. Rainfall was adequate for the first part of the 2007 growing season. Cumulative rainfall was approximately 125 mm for the first eight weeks of the growing season (Figure 2). The total rainfall for the growing season was 186 mm. In 2007, the non-irrigated treatment had approximately half the yield (2.4 Mg/ha) of the irrigation treatments (5 Mg/ha). The irrigated treatment yields were not significantly different from each other. Irrigator Pro called for irrigation to begin immediately as the rainfall began to subside (~8 weeks after planting). The soil water potential controlled treatments did not call for irrigation until about 2-3 weeks later (figure 3). Similarly near the end of the growing season, Irrigator Pro began to reduce irrigation application amount/times whereas the soil water potential controlled treatments did not. Total water applied (rainfall +irrigation) was significantly higher for the Irrigator Pro treatments than for the soil water potential controlled treatment (Table 2). In 2007, no significant differences were observed between the two Irrigator Pro treatments (whole plot management vs. each soil in a plot management). However, both Irrigator Pro treatments applied significantly more water than the treatment controlled by soil water potential measurements.

Table 1. Irrigated and non-irrigated peanut yields using Irrigator Pro and soil water potentials to schedule irrigations.

	2007		2008	
Treatment	Yield (kg/ha)	Std	Yield (kg/ha)	Std
Non-Irrigated	2448 a	277	5793 a	766
Irrigator Pro	5050 b	563	5841 a	767
Irrigator Pro by soil	4722 b	622		
Tensiometer (soil water potential)	5216 b	935	6035 a	954

Table 2. Total water for irrigated and non-irrigated peanuts.

	2007		2008	
Treatment	Total Water (mm)	Std	Yield	Std
Non-Irrigated	186	-	605	-
Irrigator Pro	509 a	47	651 a	34
Irrigator Pro by soil	503 a	53		
Tensiometer (soil water potential)	452 b	35	668 a	33

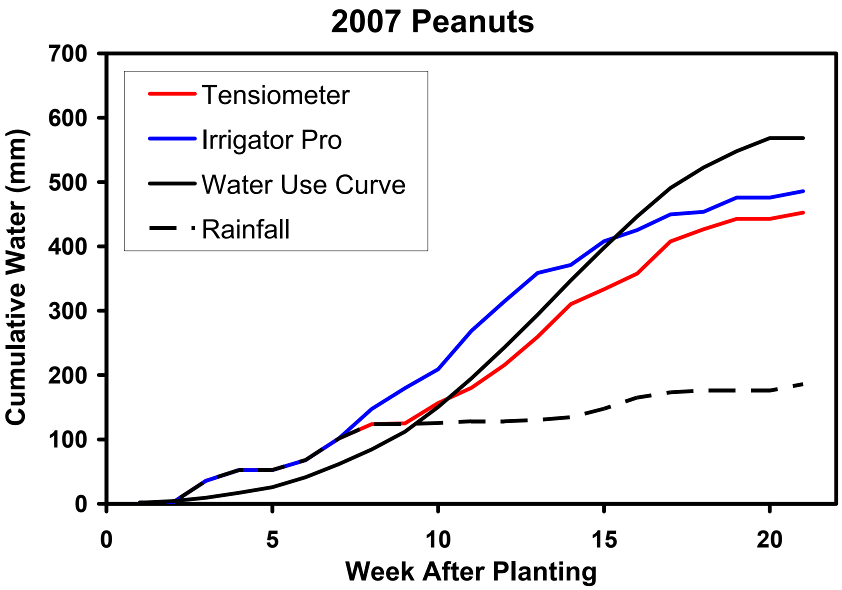

Figure 2. Total cumulative water for both non-irrigated and irrigated peanuts in 2007.

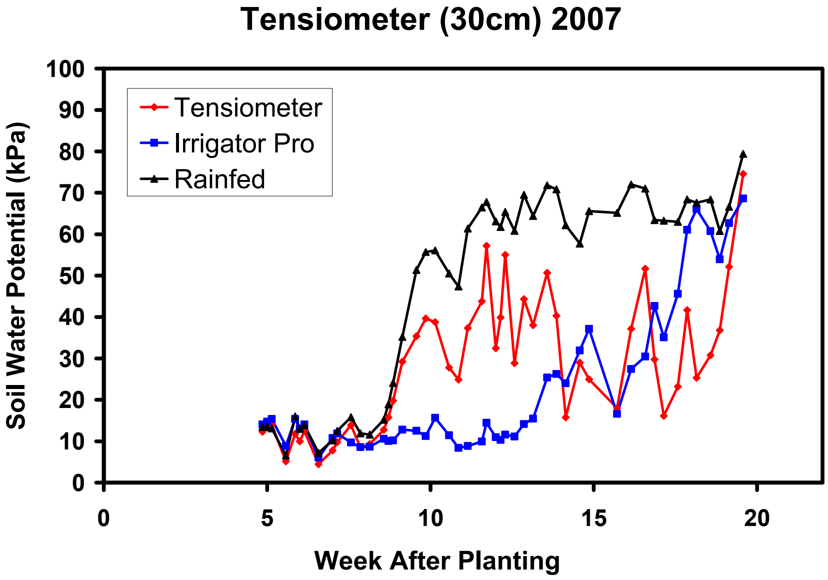

Figure 3. Soil water potentials for non-irrigated and irrigated peanut treatments in 2007.

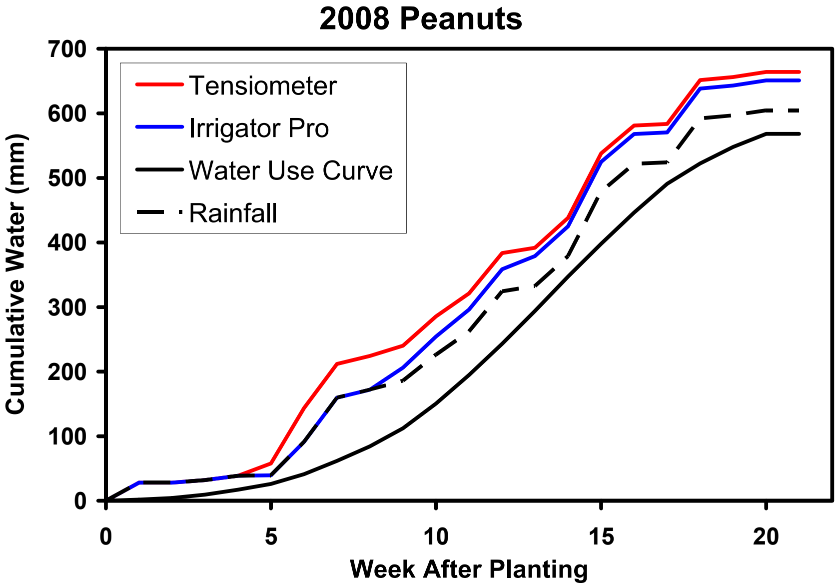

Figure 4. Total cumulative water for both non-irrigated and irrigated peanuts in 2008.

In 2008, there was much more rainfall than in 2007 and it was well distributed throughout the growing season. Total rainfall was 605 mm compared to 186 in 2007 (Table 2 and figure 4). Consequently, the soil water potential measurements under all treatments seldom exceeded -30 kPa irrigation trigger. The peanut yields reflected the favorable rainfall and distribution. Yields averaged approximately 5.9 Mg/ha across all treatments (Table 1). There were no significant differences in peanut yields among the treatments. Initial observation on using Irrigator Pro for scheduling irrigation using a variable rate system shows promise but further evaluation on refining its application for spatial application is needed.

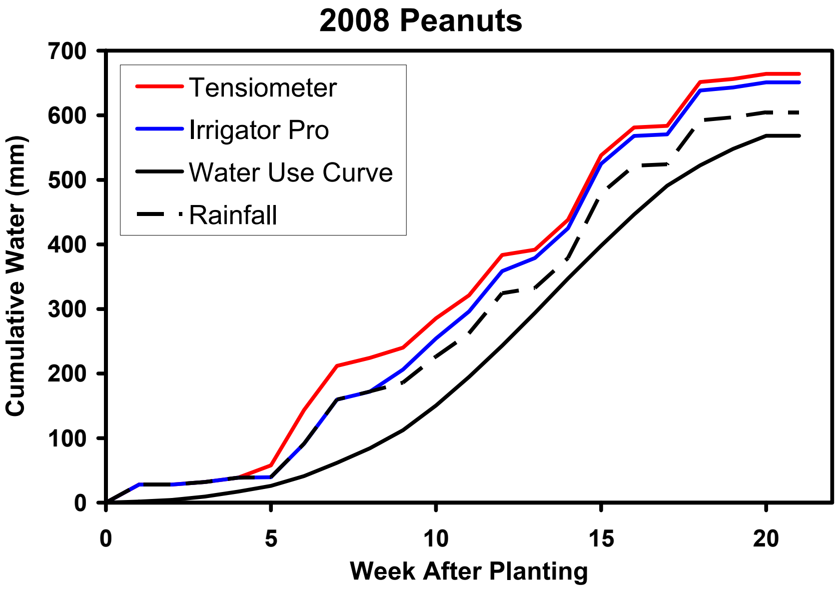

Figure 5. Cumulative water for both non-irrigated and irrigated peanuts in 2008.

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Benefits of Pressure Regulation in Irrigation

Theodore G. Santiesteban[1]

ABSTRACT

The use of pressure regulation in irrigation design can significantly improve system efficiency by limiting pressure fluctuation that reduces distribution uniformity (DU). With increasing emphasis on water and energy conservation, many systems are being designed or converted to lower pressure. As a result, system pressure variations have become a larger percentage of the total, requiring more precise regulation.

A standard irrigation design objective is to take a predetermined amount of water and apply it uniformly over a fixed area. Uncontrolled pressure fluctuations into sprinklers or emitters result in unwanted flow deviations and pattern distortions. Various types of pressure regulators are available to meet specific flow and pressure requirements. These relatively low cost devices can dramatically improve system performance. Understanding the effect that pressure control has on irrigation system performance and knowing the fundamentals of pressure regulator operation and application is essential for irrigation system designers and growers.

INTRODUCTION

The availability of water worldwide for irrigation is decreasing. Half of the world's fresh water supplies are being depleted faster then they can be replenished. Currently about 70% of the world's available fresh water supply is being used for irrigation. Several factors are driving the demand for water, the most significant of which is food production needed to feed a rapidly expanding population. Additionally, changes in population demographics, especially in the developing world, have led to a shift to higher protein diets requiring greater water inputs and further exacerbating water demand. Consequently, the agricultural community has an enormous impact on water conservation. Unfortunately, 90% of irrigation systems are based on inefficient methods of irrigation. This means that conversion of these wasteful systems to more efficient mechanized or drip systems has the potential to produce water savings of 50% or more (William Blair & Company, 2009).

Government is also playing an increasing role in the use of water and the future direction of the irrigation industry. Regulation and subsidies aimed at water conservation are driving the switch to more efficient irrigation systems. New technologies and innovations in irrigation will be used to lower cost and improve yields of not only food production but also agricultural products such as alternative fuels. Pressure regulators are at the forefront of irrigation technology and the efficient use of water resources.

BENEFITS OF PRESSURE REGULATION

Uniformity

One major reason to regulate system pressure is to maintain high uniformity. A basic irrigation design objective is to take a predetermined amount of water and apply it uniformly over a given area. Why should growers be concerned with irrigation system uniformity? Allowing uncontrolled pressure fluctuations into sprinklers or emitters will result in unwanted flow deviations. Uniform water application is necessary to maximize system efficiency (Haman and Yeager, 1998**.** Therefore,

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maintaining constant pressure throughout the irrigation system is critical for the uniform distribution of water.

The total pressure variation in a well designed irrigation system should not exceed 20%. As the irrigation industry continues to move towards more efficient lower pressure system designs, the impact of system pressure variations have become a larger percentage of the total system pressure, requiring more precise regulation.

Flow (discharge) and Pressure Relationship:

> New Flow Rate = Old Flow Rate Multiplied by the Pressure Ratio (Square Root of the New Pressure Divided by the Old Pressure)

The following simplified equation can be used for pressure ratios less than 1.5:

> The Percentage of Flow Variation Equals Half the Percentage of Pressure Variation (Sprinkler Irrigation 4th Edition). Therefore, when system pressures vary by 20%, system flow will vary by 10%.

Uniformity of water application of sprinkler irrigation systems is commonly reported as Distribution Uniformity (DU). It is an indicator of how consistent the application rates are in the system. In nursery applications a DU of 60% or below is considered low and indicates that application rates vary greatly. A system DU of 80% or greater is considered high and indicates consistent water distribution. DU is based on the low quarter of the irrigated area. For high value crops, 80% DU is a minimum (Haman and Yeager, 1998)**.**

> DU = (Average Low Quarter Depth / Overall Average Depth) x 100%

In the following example, the average seasonal irrigation requirement of Corn grown in Minnesota is 11-inches. The design parameters include impact sprinklers on a center pivot irrigating 100 acres with a system distribution uniformity of 70%..

> Irrigation Requirement = Plant requirement / Uniformity

Table 1: Irrigation requirements based on system distribution uniformity

Plant Requirement	**Uniformity**	**Irrigation Requirement**	**Gallons per Acre Inch**	**Irrigated Acres**	**Gallons/ year**
11 inches	70%	15.7 inches	27,154	100	42,631,780
11 inches	85%	12.9 inches	27,154	100	35,140,470

This example illustrates that by increasing uniformity from 70% to 85%, an 18 percent decrease in water use can be achieved (Table 1). Higher system uniformity results in less water required to irrigate the crop, lower pumping costs, reduced risk of leaching chemicals, and runoff. (Mathers 2003)

Irrigation System Considerations

System pressures will vary throughout the system due to friction loss through pipes, fittings and elevation changes. When operating conditions change from one system block or zone to another, or if different combinations of these subsets will be operated simultaneously, regulators may be required.

Mechanical move systems may have an end gun or corner arm which acts as a separate zone, and when turned on or off will dramatically change system pressure. In solid set applications, the pipe diameters and elevation do not change once the system is installed. However, mechanical move systems are not stationary and they have the potential to experience elevation (Figs. 1a, 1b) and pressure changes during operation that in turn could cause flow variations greater than 10%. Furthermore, some mechanical move systems are designed to be moved from one area to another, potentially adding additional pressure and flow variations. Proper placement of pressure regulators in these applications (scenarios) can provide constant pressures to the irrigation system, a zone, individual lateral lines, and/or any combination of positions and prevent variations from affecting the irrigation uniformity. (Clark, Stanley, and Smajstrla, 2002)

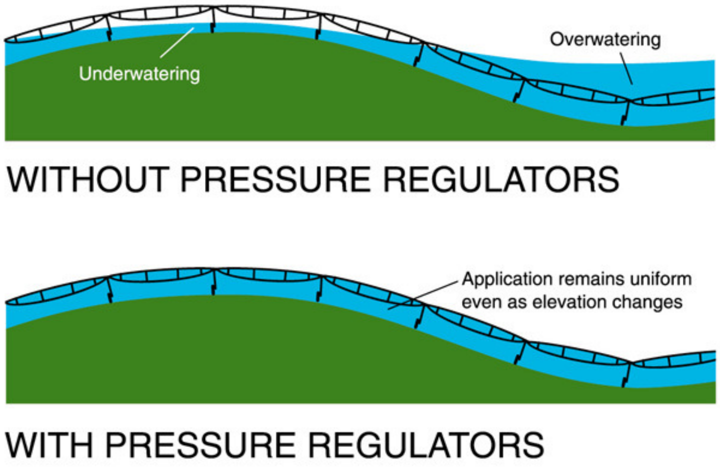


Fig. 1a: The effects of elevation on an unregulated center pivot.

Fig. 1b: A photo showing a center pivot operating across varying field elevations.

Sprinkler Considerations

Sprinkler uniformity can be affected by head spacing, flow, and pressure. Changes in pressure directly impact sprinkler flow rates resulting in variable application rates within the defined area. Poor uniformity due to flow variations is compounded by the effects of pressure on sprinkler patterns. Pressure fluctuations outside the intended system design parameters will produce pattern distortions and other irregular sprinkler operation and performance characteristics. Beyond the design pressure parameters, operating a sprinkler outside of the manufacturer's recommended ranges can produce extreme sprinkler performance abnormities and possible sprinkler or system damage. Operating pressures that are too high will generate very small droplets (fogging) susceptible to wind drift, irregularly large amounts of water near the head, and changes in rotational speed (Fig. 2a, 2b). If the pressure is too, low donut shaped patterns (Fig. 2c) and dry spots near the heads may form. The result in either case is lower sprinkler and system uniformity. (4 Haman, Smajstrla, and Pitts, 2003)

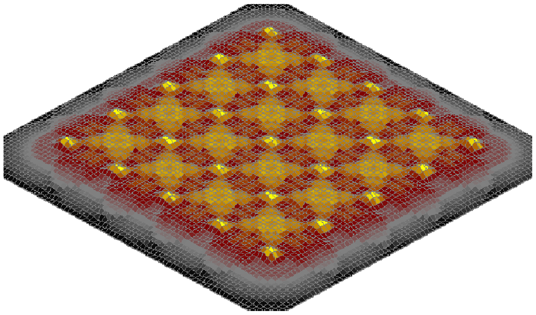
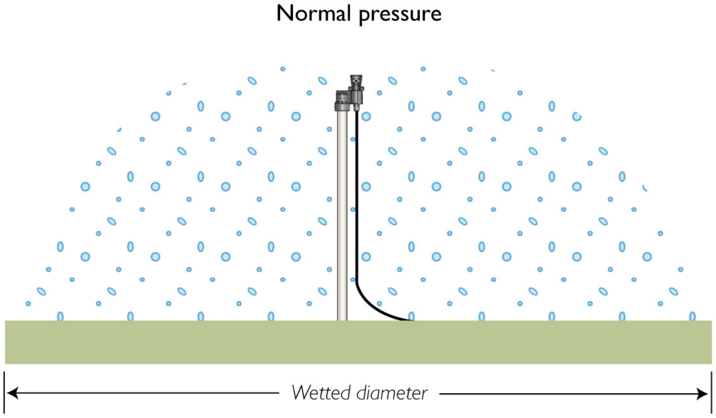


Fig. 2a: Sprinkler densogram at the design pressure showing relatively even distribution.



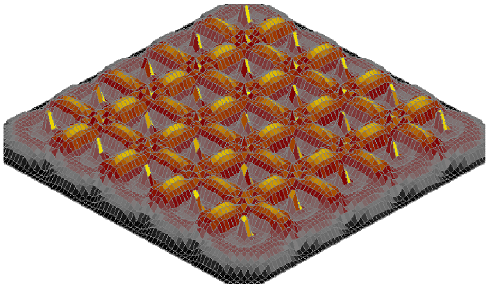


Fig. 2c: Sprinkler densogram showing donut shaped pattern distortions when the system pressure drops below allowable limits.

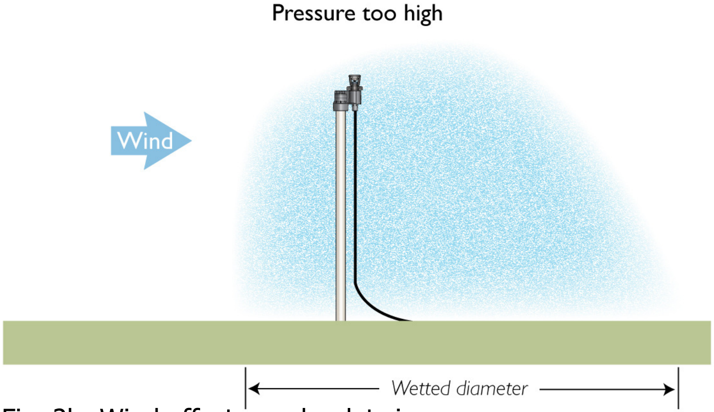


Fig. 2b: Wind effects on droplet size

Excessive pressure increases flow which can cause runoff. Irrigation systems should be designed below the minimum infiltration rate of the soil to avoid runoff. A system designed with uniformity, as one of its criteria, can help achieve this goal. (Mathers, 2003).

For Example, mini-Wobblers® irrigating a solid set field for vegetable production is designed to operate at 15 psi with a flow rate of 1.67 gpm on a spacing of 25 x 25 ft. yielding an application rate of 0.25 inches per hour over a defined area of 350 ft. x 350 ft. The infiltration rate of the soil has been determined to be 0.25 inches per hour.   However, one of the laterals has developed a leak and is shut off for repair but the zone is still activated. This results in an increase in pressure of 20% which translates into 10% increase of sprinkler flow rate, thus raising the application rate to 0.28 inches per hour. Exceeding the soil infiltration rate increases the potential for runoff." (Mathers 2005)

System Life Expectancy

When system pressure exceeds the manufactures recommended range, some system components may fail or exhibit unacceptable performance characteristics. Most low-volume tubing or tape products have a maximum pressure rating to prevent product damage or failure. Pressure compensating products require a specific inlet pressure range to function properly, which if exceeded, will cause flow variation to exceed design tolerances.

Pressure regulators may be required if the pressure produced by the pump is too large or if zones vary greatly in flow. Often, when a system is retrofitted with lower pressure sprinklers, the pump portion of the existing system is not changed. This could cause the system to operate at pressures which are excessive for the new components. The pump must deliver the amount of water required in the largest zone at the pressure required. If the zones are not equally sized, the pump will deliver higher pressure at the smaller discharges required by these zones. Pressure regulators must be used to provide the lower pressure required for lateral lines or other low pressure system components.

To ensure that irrigation systems will function safely, system components must be properly pressure-rated to match system pressure. (Smajstrla, Zazueta, and, Haman, 2002) In some cases this is not possible without the use of pressure regulators. Center pivot systems fitted with low pressure sprinkler packages may experience excessive pressures at the pivot point that exceed the drop hose rating. Pressure regulators can be used upstream of the hose to prevent premature failure (Fig. 3).

Fig. 3: Pressure regulators installed upstream of drop hoses.

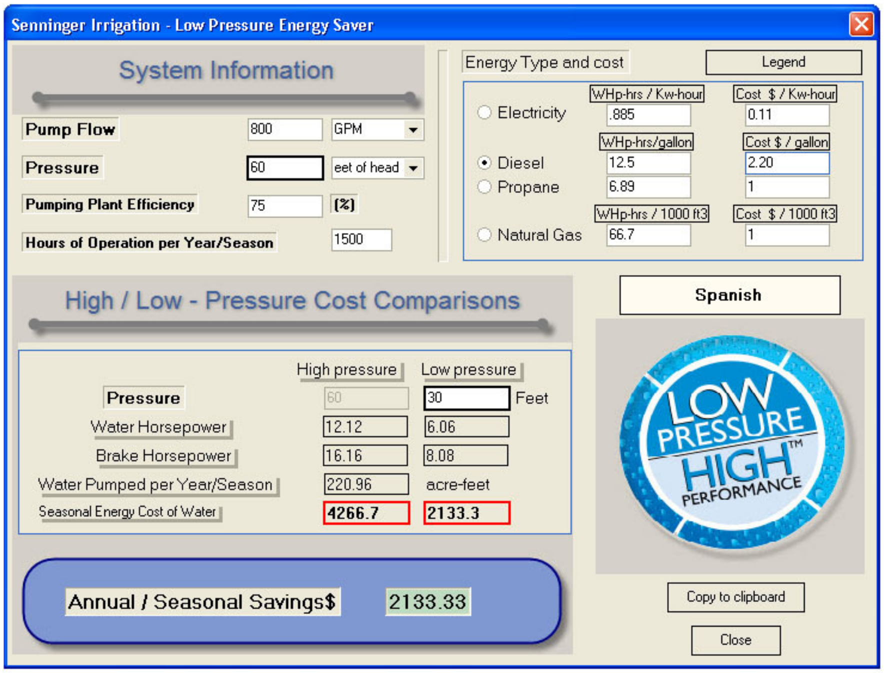
Mechanical move system components have a range of pressures that provide long life and optimal performance. Exceeding the manufacturers recommended pressure can produce droplets that are highly susceptible to evaporation and wind drift. Additionally, nozzle steam velocities are increased causing accelerated sprinkler wear, especially on spray pads that are impacted continually in the same location. As system pressure is reduced stream velocity is also reduced and product longevity is increased. Adhering to manufacturer's maximum and minimum pressure recommendations is critical for long-term system life and optimum operation.

Not Everyone Needs Pressure Regulators

Acceptable pressure control of some systems can be achieved without pressure regulators. Factors affecting appropriateness of regulator use include; system design, elevation, and cost constraints. Pressure control on a flat ground irrigation installation with single or equal zones can be achieved through pipe sizing. In some instances flow control can be used in place of pressure regulation. However, pressure regulators are an important tool for optimizing system efficiency and cost.

ECONOMIC CONSIDERATIONS

Operational cost savings achieved though lower system pressures and higher system efficiency can be seen most visibly and directly in the form of lower pumping costs. The use of pressure regulators plays an important role in cost savings generated though lower energy systems. (Fig. 4). Lowering operating pressure saves energy. With the high cost of electricity and fuel, that translates to saving money. To take full economic advantage of lower pressure systems, uniformity of flow must be maintained. Irrigation systems operating at lower pressures are more susceptible to pressure variations. Pressure Regulators can be used to maintain consistent pressure resulting in uniform flow and better system efficiency.



Senninger Irrigation - Low Pressure Energy Saver

System Information

Pump Flow 800 GPM
Pressure 60 eet of head
Pumping Plant Efficiency 75 (%)
Hours of Operation per Year/Season 1500

Energy Type and cost

	WHp-hrs / Kw-hour	Cost $ / Kw-hour
○ Electricity	.885	0.11
	WHp-hrs/gallon	Cost $ / gallon
● Diesel	12.5	2.20
○ Propane	6.89	1
	WHp-hrs / 1000 ft3	Cost $ / 1000 ft3
○ Natural Gas	66.7	1

High / Low - Pressure Cost Comparisons

	High pressure	Low pressure	
Pressure	60	30	Feet
Water Horsepower	12.12	6.06	
Brake Horsepower	16.16	8.08	
Water Pumped per Year/Season	220.96	acre-feet	
Seasonal Energy Cost of Water	4266.7	2133.3	

Annual / Seasonal Savings$ 2133.33

Fig. 4: Energy savings calculator available online

The Energy Saver calculator example shows that upgrading a conventional high pressure system to a more efficient low pressure system can save $2133/year. This represents a relatively short payback on the upgrade investment for a typical mechanical move sprinkler package with pressure regulators.

Labor availability and cost are other considerations. Manual valves will need to be adjusted to compensate for the pressure variations in an irrigation system, without pressure regulators, that experiences pressure fluctuations. Pressure regulators automatically regulate the pressure negating the need for manual system adjustment and the potential for human error that could cause non-uniform system performance and/or system damage.

Poor uniformity caused by pressure fluctuations will affect crop yield and/or quality. Under watering leads to water stress, while the over-irrigated areas will experience higher potential for disease, leaching, and/or runoff. Either case will negatively affect return on investment. Non-uniform irrigation systems are over-irrigated to compensate for the poor DU which directly increases pumping cost. Leaching of chemicals increases cost and has the potential of polluting ground water. Run-off wastes water and applied chemicals, while simultaneously striping soil which also increases cost. (Smajstrla, Zazueta, and Haman, 2002)

The scarcity of water in some regions has brought with it water restrictions. When existing irrigation systems, operating at higher pressures and lower uniformities, do not functioning adequately under new water usage guidelines, system upgrades will be required. Government programs like EQIP (Environmental Quality Incentives Program) incentivizes growers to upgrade older systems by providing technical and cost-share assistance to improve irrigation efficiency. Water conserving irrigation systems, pipelines and conveyance systems may be cost-shared and incentive payments are available for producers who engage in and document improvements in water use efficiency (NRCS website).

The majority of mechanized irrigation systems installed today deliver water at relatively low pressure to crops via hoses that drop down from the systems mainline. Conventional high-pressure mechanized systems are typically about 60%-75% water efficient (meaning 60%-75% of the dispensed water ends up in the crop root zone). End guns operate at relatively high pressures which require large energy inputs per unit of water delivered. (Smajstrla, Clark and Haman) Other high pressure sprinklers include, impact sprinklers or unregulated spray or rotary type sprinklers with high inlet pressures. Lower pressure, LEPA and Drip, systems are 95%-97% (Amosson, New, Almas, Bretz, and Marek, 2002) water efficient. In addition, given the systems run at lower pressure, reduced pumping needs result in energy savings of 20%-50%. (William Blair & Company, 2009)

The prohibitive cost of obtaining perfect uniformity requires that a balance be struck between the value of the natural resources wasted and the increased cost of achieving greater application uniformity. Adopting new irrigation technology is considered feasible when the benefits of doing so are lower than the investment costs (Amosson, New, Almas, Bretz, Marek 2002). When taking into account pumping, labor, and other irrigation system operating costs, the total cost of a well designed system, with greater uniformity, will almost always be lower than for a poorly designed irrigation system. (Smajstrla, Zazueta, and Haman)

PRESSURE REGULATORS DEFINED

An in-line pressure regulator acts very much like an ordinary valve. The big difference is that a pressure regulator does not require constant manual adjustment of the water flow. Inlet pressure is reduced by reduction in the flow path inside the regulator.

Fig. 5: Various pressure regulator models and flow ratings.

In throttling stem type regulators (Fig. 6), flow enters through the inlet side and travels past a fixed seat and through a hollow cylinder (throttling stem) that moves in response to changes in back pressure. The spring tends to hold the regulator flow area open, while outlet pressure tends to close it. This duel between spring load and outlet pressure ends in a draw. The result is a constant preset outlet pressure determined by the strength of the spring (M. Healy, 2009).

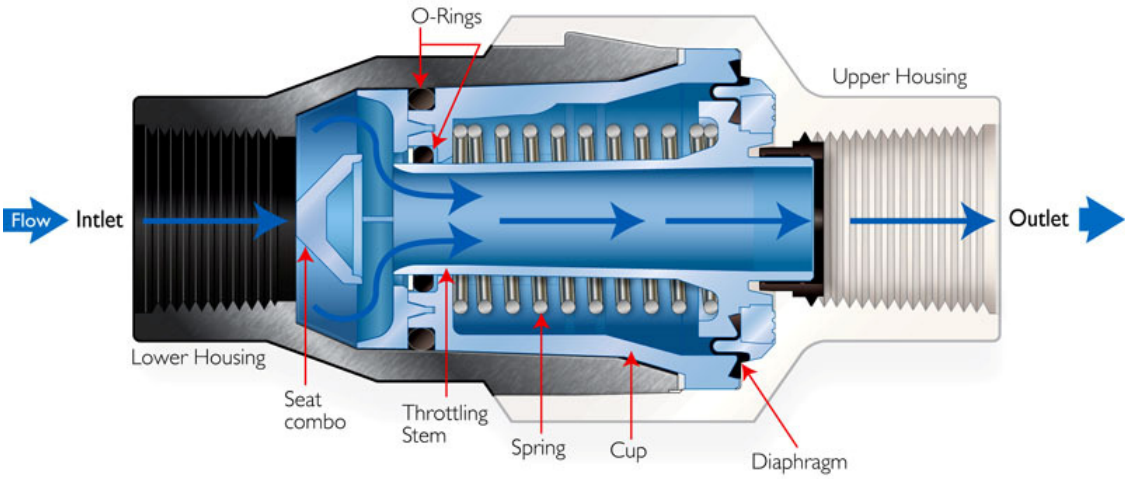


Fig.6: Cut-away of a throttling stem style pressure regulator.

To function properly a pressure regulator should have an inlet pressure at least five psi above the expected outlet pressure, and flow should match the manufactures stated flow range on the outside of the regulator. For example, a 10 psi regulator will require 15 psi inlet pressure for regulation to occur. The use of accurate pressure regulators ahead of all sprinkling devices will help provide uniform water distribution, even with varying regulator inlet pressure.

Flow control nozzle vs. Pressure Regulation

A pressure regulator controls pressure regardless of variation in flow, while a flow control nozzle meters the flow rate regardless of pressure variations. Pressure regulators maintain a preset outlet pressure regardless of inlet pressure and utilize an applicator's fixed nozzle orifice size to correspond to the desired flow. Flow control nozzles utilize a flexible disk with an orifice that changes shape as pressure fluctuates. As upstream pressure increases the disk orifice becomes smaller due to outward flexing of the disk (Fig. 7). However, as opposed to a pressure regulator, activation of the flow control device does not usually occur until upstream pressure exceeds a threshold pressure. Threshold pressure ranges from 20 to 50 psi depending on flow. Typical flow control nozzles require a smaller inlet pressure range than pressure regulators. (Mathers 2003)

Flow Control Nozzle

Unregulated flow

Regulated flow

Fig. 7: Flow control nozzle before and during activation.

A common question is when to use pressure regulation and when to use flow control. Many factors will determine their use, such as; application (accuracy requirements), cost constraints, topography, and system configuration. Pressure regulators are generally more accurate than flow control nozzles by virtue of their design and have a wider operational window. The use flow control is relatively limited and cannot be selected for specific field situations. Rather, they are selected to operate within a range of operating pressures. This limits the capability of a flow control nozzles to accurately regulate flow rate. (Kranz, Irmak, Martin, Yonts, 2007) If an irrigation system has pressures differences greater than 20% of the design pressure, pressure regulators or flow control should be used.

Regulator Selection

Not only is the type/model of pressure regulator important in the selection process but also the manufacturer. It isn't just enough to select a low pressure regulator for efficient use of water and energy. High quality low pressure regulators must be matched with low pressure sprinklers to produce the optimum results. (Von Bernuth and Baird 1987)

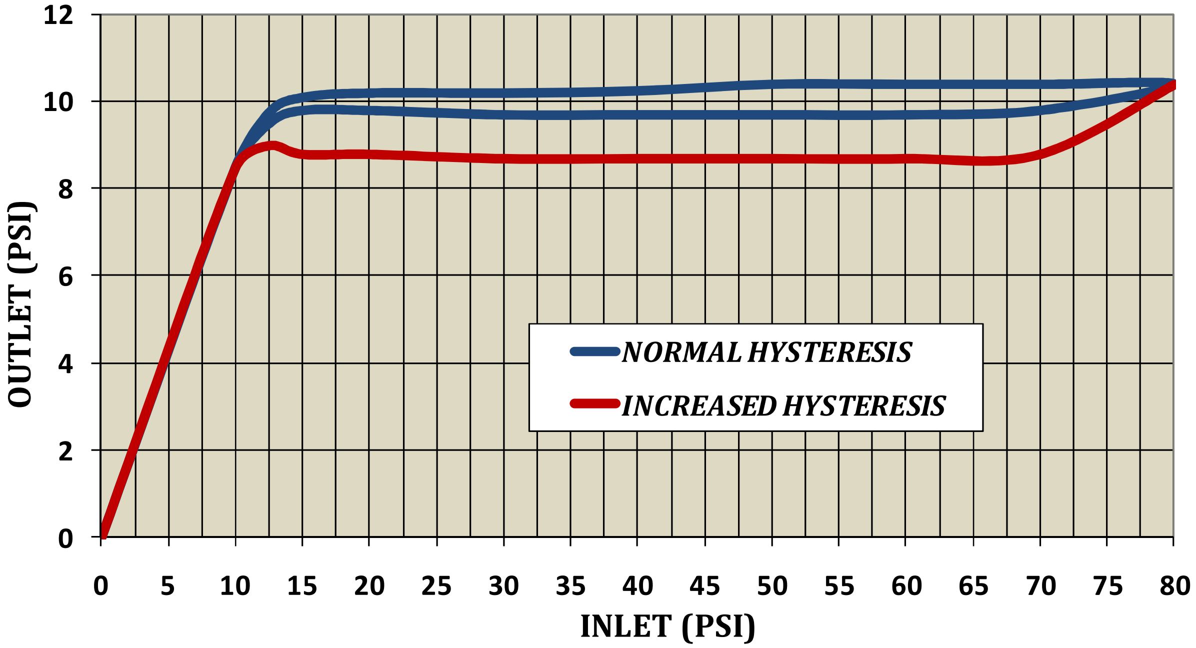


Fig. 8: Typical hysteresis in a pressure regulator

In a valve mechanism such as a pressure regulator, hysteresis (Fig. 8) is the phenomenon which can be described as drag or lag. Excessive friction loss or a poorly designed pressure regulator diminishes its ability to accurately respond to the pressure changes that it was designed to control. In a poorly designed pressure regulator, when inlet pressure increases, higher-than-desired outlet pressures will result. When inlet pressure declines, the friction loss factor can cause pressures to drop below the operating pressure resulting in a pressure regulator that doesn't regulate at all. (Elliott, 1997)

Regulators with high friction loss also require higher inlet pressures to operate thus requiring more energy with the potential consequence of compromising system flow. In some regions, flow can dramatically fall off due to well draw-down. As draw-down occurs system pressure will begin to fall, and because the nozzle orifice sizes are fixed, flow will also decrease. As draw-down continues, the pump may no longer be able to fill the irrigation lines resulting in portions of the system not emitting water. Selecting the right regulator for specific applications is critical for good system performance.

CONCLUSION

Pressure regulators can be used to significantly improve irrigation system efficiency resulting in lower costs, improved crop yields, reduced runoff, and conserved water. Pressure regulation limits pressure fluctuations that reduce distribution uniformity (DU). As the emphasis on water and energy conservation has increased, many irrigation systems are being designed or converted to lower pressure. This has resulted in system pressure fluctuations being a larger percentage of the total pressure, requiring more precise regulation. However, not all pressure regulators provide the precise regulation required for optimum system efficiency. Selecting the right regulator for the application is critical for consistent long term system operation. High quality low pressure regulators must be matched with low pressure sprinklers to produce optimum results. Greater awareness, through education, of the impact that uncontrolled pressure has on system performance and how to properly apply pressure regulators is essential for resource conservation. Pressure regulators are an important tool to ensure our future ability to provide food, fiber, and fuel for a hungry world.

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Soil & Nutrient Losses from Small Sprinkler & Furrow Irrigated Watersheds in Southern Idaho

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Abstract. *Sediment and associated nutrients flowing to the Snake River with furrow irrigation runoff and unused irrigation water have been a concern in the Twin Falls irrigation tract in southern Idaho. Converting furrow irrigated fields to sprinkler irrigation is one practice that has been promoted, and received financial assistance, to reduce sediment loss. Five small watersheds (330 to 1480 acres) with 10 to 70% sprinkler irrigation were monitored from 2005 to 2008 to determine if converting to sprinkler irrigation reduced sediment and nutrient losses from these watersheds. Eliminating runoff from furrow irrigated fields by converting to sprinkler irrigation will reduce sediment and nutrient losses from fields. However, there were no significant correlations between the amount of sprinkler irrigation and the sediment or nutrient loads from these watersheds. Potential reasons for these results are the flow rate allocation system used by the TFCC, the amount and location of furrow irrigated fields in each watershed, and the management of furrow irrigated fields within each watershed. One significant correlation was decreasing dissolved phosphorus concentrations as relative amount of sprinkler irrigated land increased, presumably because less water flowed across fields in furrows as sprinkler irrigated area increased. A water quality model for irrigated watersheds is needed for more thorough assessment of the variety conditions and management practices within these watersheds.*

Keywords. Irrigation Erosion, Furrow Irrigation, Sprinkler Irrigation, Best Management Practices.

Introduction

Soil erosion from furrow irrigated fields has been the primary natural resources concern in the Twin Falls irrigation tract in southern Idaho since the 1970's. Water flowing in irrigation furrows detaches and transports soil. It is impractical to contain irrigation runoff on furrow irrigated fields in this area because field slopes are typically 1 to 2% and some irrigation runoff is desired to achieve acceptable irrigation uniformity. Berg and Carter (1980) found that 20 to 50% of applied irrigation water ran off furrow irrigated fields in the Twin Falls tract. Soil loss from these fields varied from 0.4 to 63 ton/acre annually. In a more recent study, annual soil loss of 0.9 to 15 ton/acre was measured on six commercial furrow irrigated fields (Bjorneberg et al., 2007). In 1971, Carter et al. (1974) measured a net loss of 460 lb/a of sediment from the watershed during the irrigation season (May through September). Eroded sediment and associated nutrients return to the Snake River with furrow irrigation runoff and unused irrigation water. The NRCS provided more than $4 million through the Environmental Quality Incentive Program (EQIP) for conservation practices in this area between 2002 and 2006, with approximately 90% of these funds used to convert from furrow irrigation to sprinkler irrigation (Bjorneberg et al, 2008).

The Upper Snake Rock (USR) Watershed was one of eight NRCS Special Emphasis watersheds selected for the Conservation Effects Assessment Project (CEAP) in 2004. One primary objective of this project was to determine if converting from furrow irrigation to sprinkler irrigation improved surface water quality in the watershed. Monitoring for this project focused on the Twin Falls irrigation tract, a 202,000 acre watershed that receives irrigation water from the Snake River through canals managed by the Twin Falls Canal Company (TFCC). The objective of this paper is to compare sediment and nutrient losses from five small watersheds within the Twin Falls tract that have different amounts of sprinkler irrigation. We hypothesized that watersheds with greater amounts of sprinkler irrigation will lose less sediment and nutrients.

Materials and Methods

Five small watersheds within the Twin Falls irrigation tract were chosen for monitoring based on each having a well defined inflow boundary and a single outlet. It is common within the Twin Falls irrigation tract for unused irrigation water and field runoff to be diverted from drainage channels to other fields, making the surface water hydrology very complex in some areas. Field runoff was not re-diverted within these sub-watersheds, which varied from 330 to 1480 acres and had 10 to 70% of the cropland sprinkler irrigated in 2005 (table 1). Soils in all watersheds were silt loams, predominantly Portneuf silt loam. One watershed (EC) contained subsurface drains that continued to flow after the irrigation season until early January.

Table 1. Watershed Characteristics.

		Sprinkler Irrigated Area		Average
	Size	2005	2008	Field Slope
Watershed	(acre)	(%)	(%)	(%)
EC	1480	11	22	2 to 8
PC1	600	10	10	0 to 2
PC2	1020	41	52	0 to 2
TF1	430	19	33	2 to 4
TF3	330	63	70	2 to 4

The five watersheds were monitored from 2005 to 2008 during the irrigation season (May 1 to September 30). Crop production and irrigation practices on the five sub-watersheds were recorded through monthly field surveys during the irrigation season. Outflow from each sub-watershed was measured with a flume. A data logger with a pressure transducer measured water stage every minute and recorded the hourly average stage and flow rate. The data logger also calculated cumulative flow volume every minute to trigger water sample collection. An automatic sampler, controlled by the data logger, collected flow proportional samples with a goal of 4 to 5 samples bottles per week. Ten, 0.2-L sub-samples were composited in each 2 L sample bottle. The data logger triggered the sampler after 650 to 3000 m^3 of flow. These trigger volumes were equivalent to 0.2 to 0.6 mm of flow from each sub-watershed. The data loggers also recorded cumulative flow volume for each sub-sample and sample.

All monitoring sites were visited weekly while water was flowing to collect water samples, record flow stage and download flow data. Water samples were refrigerated until processed the day after collection. During sample processing, samples were stirred for 1 to 2 min before measuring pH and electrical conductivity (EC). A 50 ml aliquot was taken for total N and P analysis. A second 20 ml aliquot was filtered (0.45 micron) and analyzed for dissolved nutrients (NO_3, P). A third aliquot was used to determine sediment concentration by filtering a known volume (approximately 100 ml) through 0.45 micron filter paper and weighing the dried filter paper. The filtered water sample was analyzed by inductively coupled plasma-optical emission spectroscopy (ICP-OES) for P and by flow injection analysis (FIA) for NO_3-N concentrations. An aliquot (~25 ml) of the unfiltered water sample was digested with a Kjeldahl procedure (USEPA, 1983) and analyzed by ICP-OES for total P and by FIA for NH_4-N for total N.

Flow volume for each water sample was multiplied by parameter concentrations from laboratory analysis to calculate mass loads. Loads were summed over the irrigation season and the month of July. Flow-weighted concentrations were calculated by dividing the mass load for a time period by the total flow volume for the same period.

Linear correlations were used to compare water quality parameters with the relative amount of sprinkler irrigation in each watershed (i.e. percent sprinkler irrigated area). Water quality parameters were also correlated with the relative amount of furrow irrigated row crops in each watershed, assuming that the greatest sediment loss occurs from furrow irrigated row crop fields. Correlation coefficients (r) were considered significant for $P<0.05$ (Little and Hills, 1978).

We also evaluated the effectiveness of converting to sprinkler irrigation by comparing predicted soil loss under current conditions with predicted soil loss assuming the entire watershed was furrow irrigated. Soil loss from furrow irrigated fields was predicted with the SISL model (Bjorneberg, et al., 2007). The SISL model is an empirical model with form similar to the Universal Soil Loss Equation (USLE). A base soil loss value is multiplied by several factors to account for variations in soil erodibility, previous crop, conservation practices, and irrigation management.

Results and Discussion

Watershed outflow was lowest in 2005 (Table 2) because above normal precipitation in the watersheds reduced the need for irrigation in May. Furthermore, below normal snowpack reduced water available for irrigation and caused the TFCC to restrict irrigation allocations during the summer. Net water use for watersheds (inflow-outflow) could not be calculated because watershed inflow data have not been analyzed yet. Inflow will be determined from daily TFCC records for each headgate delivering water to fields in these watersheds.

Table 2. Measures flow, sediment load and dissolved phosphorus load flowing from watersheds during 2005-2008.

Watershed	2005	2006	2007	2008
	----------------- Watershed Outflow (ft) -----------------			
EC	1.05	2.00	1.68	1.51
PC1	0.43	0.60	0.64	0.49
PC2	1.50	1.87	1.84	1.56
TF1	0.73	1.21	1.54	1.91
TF3	0.79	1.48	0.73	0.89
	----------------- Sediment Load (lb/acre) -----------------			
EC	1218	1945	1527	2106
PC1	694	1067	474	840
PC2	1487	2328	1045	774
TF1	2011	8406	4516	9062
TF3	1756	6548	1573	4644
	---------- Dissolved Phosphorus Load (lb/acre) ----------			
EC	0.42	0.36	0.47	0.42
PC1	0.19	0.12	0.16	0.16
PC2	0.48	0.34	0.39	0.34
TF1	0.45	0.42	0.56	0.96
TF3	0.31	0.40	0.20	0.18

There were no statistically significant linear correlations between the relative amount of sprinkler irrigation in a watershed and the amount of water flowing from the watershed during the four irrigation seasons for individual watersheds or all five watersheds combined (data not shown). Watershed outflow also did not correlate with the relative amount of sprinkler irrigation during July when irrigation demand was greatest (Figure 1). Outflow could be watershed dependent so combining results from five watersheds would include factors in addition to irrigation type that could affect watershed outflow. However, analyzing each watershed independently did not result in any significant correlations ($-0.24<r<0.81$). While correlations were not significant for individual watersheds, the general trends indicated greater flow as sprinkler irrigated area increased ($r>0$) in four of the watersheds. One possible reason for this trend is that the TFCC allocates water on a flow rate basis, not volume basis, so farmers have little incentive to stop water delivery when they are not irrigating. The flow rate allocation is used because the original TFCC water rights are natural flow rights in the Snake River. On sprinkler irrigated fields, irrigation water flows from the headgate into a pond where it is pumped to the sprinkler system. When the sprinkler system is not running, water often spills from the pond and flows through the watershed with runoff from furrow irrigated fields, especially in the spring and fall when irrigation demand is lower. In addition, much of the outflow from these watersheds is re-diverted to other fields within the Twin Falls tract so the TFCC is not concerned about this unused water.

Sediment loads in water flowing from these watersheds varied considerably each year, especially for TF1 and TF3 (Table 2). Similar to watershed outflow, sediment load was not significantly correlated with the relative amounts of sprinkler irrigation during July ($r=0.15$) or during the irrigation season ($r=0.28$). The positive correlation coefficients indicate that sediment loss tended to increase as sprinkler irrigated area increased. This was not expected because converting from furrow irrigation to sprinkler irrigation reduces soil loss from individual fields by eliminating irrigation runoff. Part of the variability was likely caused by the variability in watershed outflow. Correlating flow weighted sediment concentration instead of sediment load did not improve the correlations for July (Figure 2) or the irrigation season ($r=0.30$).

One possible explanation for the unexpected trend in sediment load is the amount of furrow irrigated row-crops in each watershed. Table 3 shows the correlation coefficients between the percent furrow irrigated area in each watershed versus the flow-weighted sediment concentration or sediment load in watershed outflow. Two watersheds (PC2 and TF3) have good correlations between furrow irrigated row crop area and sediment concentration or load. These two watersheds also have the greatest amount of sprinkler irrigation (Table 1). Positive correlation coefficients indicate that sediment concentration or load increased as the amount of furrow irrigated row crops increased.

The location of the furrow irrigated fields within each watershed will potentially affect sediment load as some sediment may deposit in channels before reaching the watershed outlet. TF3, for example, had dry bean planted in the furrow irrigated field adjacent to the watershed outlet in 2006 when sediment load was two to four times greater than the others years (Table 2). An irrigated watershed model is needed to more fully consider the various combinations of irrigation systems and crop types within each watershed.

Table 3. Correlation coefficients between furrow irrigated row crop area and sediment concentration or load flow from the watershed during the irrigation season.

	Correlation Coefficient for Furrow Irrigated Row Crop Area vs.	
Watershed	Sediment Concentration	Sediment Load
EC	-0.42	-0.26
PC1	-0.21	0.27
PC2	0.90	0.80
TF1	0.28	-0.13
TF3	0.63	0.94

Coefficients are significant at P=0.10 if r>0.90 for n=4.

Total phosphorus (P) load was directly related to sediment load during the irrigation season (r=0.99) and during July (r=0.99), because 70 to 90% of the total P was associated with soil particles. Thus, total P followed the same trends as sediment. There was a significant correlation between percent sprinkler irrigated area and flow weighted dissolved P concentrations in July (Figure 3). Dissolved P concentration decreased as the relative amount of sprinkler irrigation increased. A similar trend occurred during the irrigation season but the correlation was not significant (r=-0.22). Dissolved P concentrations increase as water flows across the field in furrows (Bjorneberg et al., 2006) so reducing the furrow irrigated area should reduce dissolved P concentrations. The dissolved P load, however, did not correlate with the relative amount of sprinkler irrigation, probably because flow was not related to the amount of sprinkler irrigation in each watershed.

Furrow irrigation management is another potential reason for the lack of significant correlations between sediment or nutrient loads and sprinkler irrigation. One poorly managed furrow irrigated field can add more sediment to the irrigation return flow than is removed by converting fields to sprinkler irrigation. It is also possible that the better irrigation managers have tended to convert to sprinkler irrigation.

The SISL model was applied to furrow irrigated fields in PC1, TF1 and TF3 to estimate annual soil loss from each field and the entire watershed assuming no deposition before the watershed outlet. Predicted sediment load correlated reasonably well with measured sediment load (Figure 4) considering the simplicity of the SISL model and this analysis. SISL predicted sediment load was about four times greater than measured load for PC1 and twice for TF1 during the four irrigation seasons. Predicted sediment load was only 50% greater than measured for TF3, indicating that furrow irrigation erosion was greater or sediment deposition was less in this watershed, assuming SISL predictions are representative of actual soil loss. The only time measured sediment load exceeded predicted load was for TF3 in 2006, when the furrow irrigated field adjacent to the watershed outlet was planted to dry bean.

Conclusion

Eliminating runoff from furrow irrigated fields by converting to sprinkler irrigation will reduce sediment and nutrient losses from fields. However, simple linear regressions with data from five small watersheds during four irrigation seasons did result in significant correlations between the amount of sprinkler irrigation and the sediment and nutrient loads from these watersheds. Potential reasons for these results are the flow rate allocation system used by the TFCC, the amount and location of furrow irrigated fields in each watershed, and furrow irrigation management within each watershed. One significant correlation was decreasing dissolved phosphorus concentrations as relative amount of sprinkler irrigated land increased. This presumably occurred because less water flowed across fields in furrows as sprinkler irrigated area increased.

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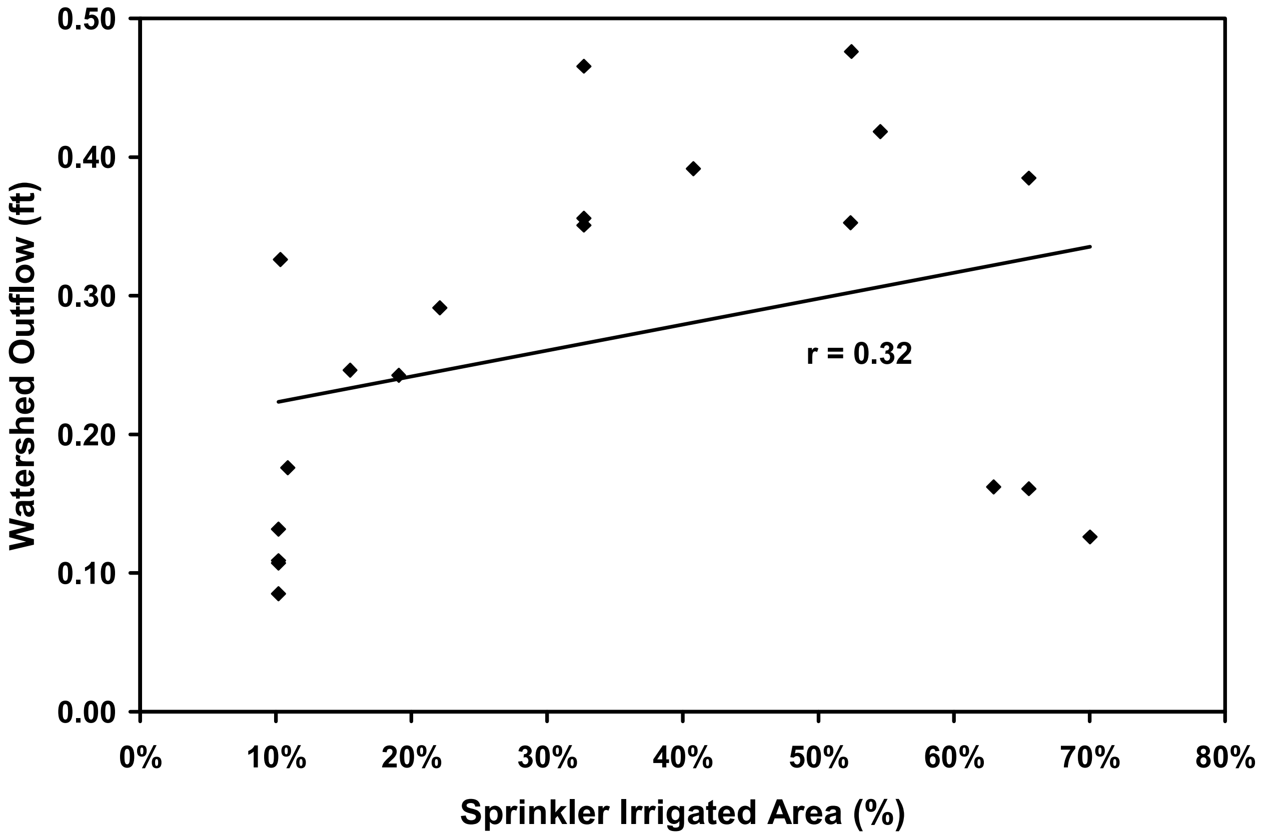

Figure 1. Correlation between sprinkler irrigated area and watershed outflow during July for 2005 to 2008.

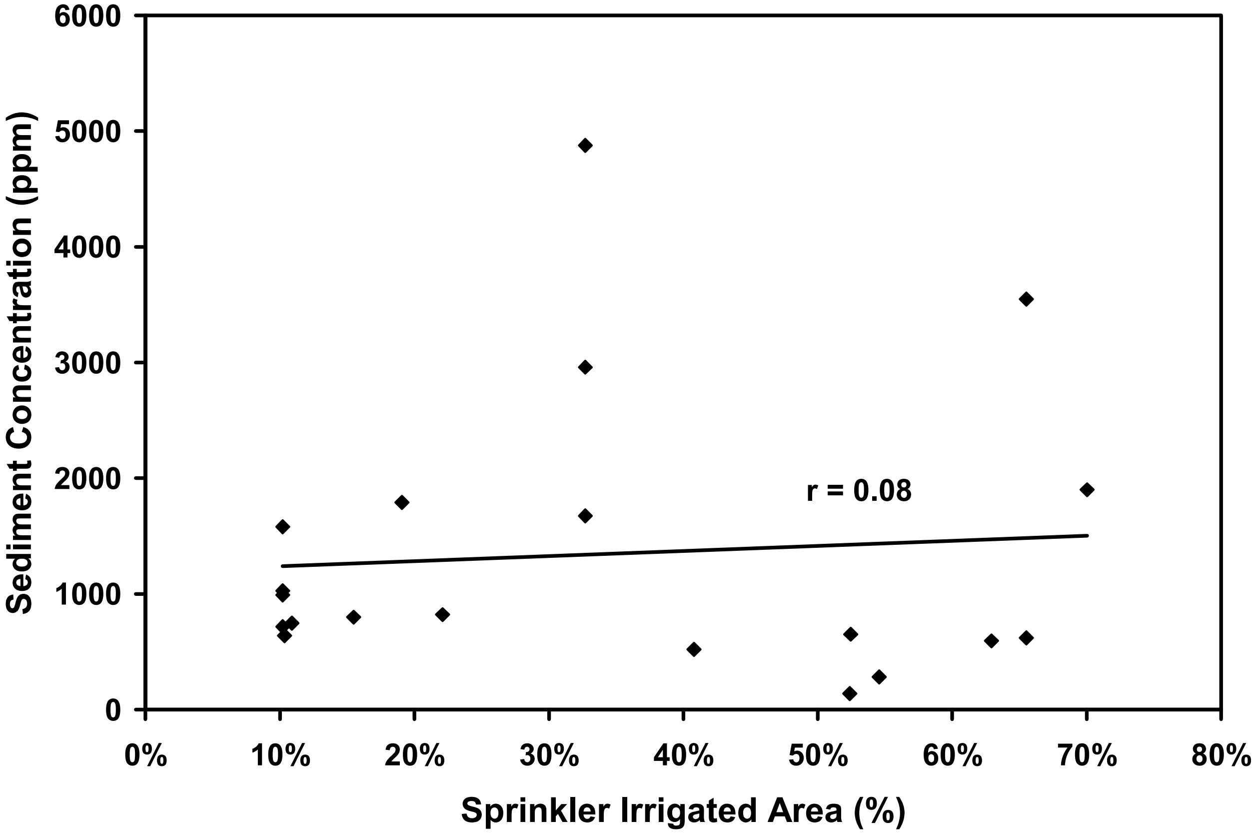

Figure 2. Correlation between sprinkler irrigated area and flow weighted sediment concentration during July for 2005 to 2008.

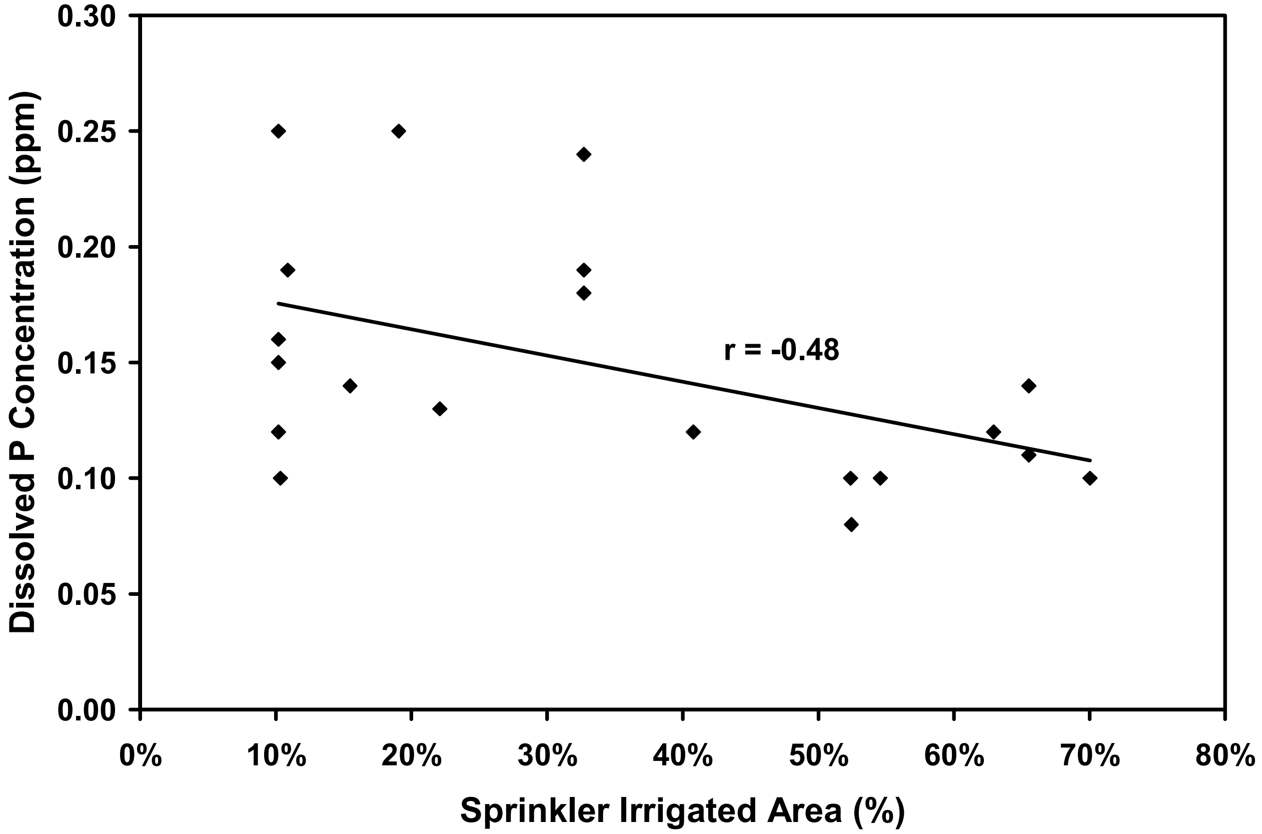

Figure 3. Correlation between sprinkler irrigated area and flow weighted dissolved phosphorus concentration during July for 2005 to 2008. (r = -0.48 significant at $P<0.05$)

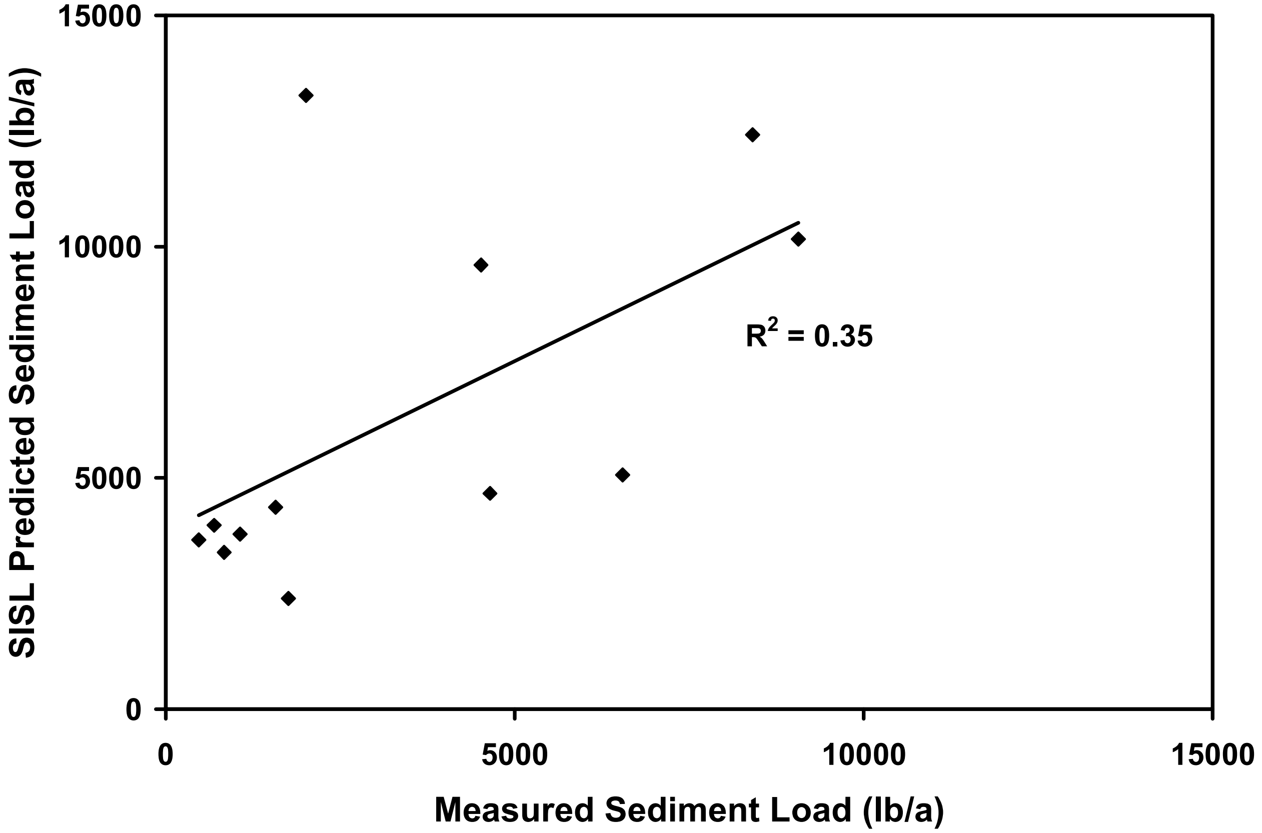

Figure 4. Measured versus SISL predicted sediment load for PC1, TF1 and TF3 watersheds for 2005 to 2008. (R^2=0.35 is significant at $P<0.05$)

Irrigation control with feedback loops

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Abstract

Applying excessive irrigation amounts is common. There is a need for a common tool which indicates sufficiency of added amount of water. Sufficient irrigation amounts is that amount that which would result in wetting the soil profile down to the bottom of the active root zone up to the water content of field capacity. Use of this definition as a control objective is problematic since this result is reached only after cessation of irrigation.

We define an irrigation objective as the depth of the wetting front to stop irrigation so that the final depth of the redistribution front would stop at the bottom of the root zone. We developed algorithms that form a closed feedback loop with a learning trial and error procedure that helps to find the optimal depth of the wetting front to stop irrigation. An input to the system is the planned final depth of the redistribution front. The system then conducts a series of trial and error field tests where a wetting front depth to stop irrigation is selected and retested. The measured final depth of the redistribution front is compared with the planned final depth. Successive corrections of next depth of the wetting front are made until the planned final redistribution depth is reached.

A dedicated wetting depth probe to track the location of the wetting and drainage fronts is presented. Also, the logic sequence for selection of the optimal wetting depth to stop irrigation and the results from a series of field trials are presented. The irrigation control with feedback was tested under real conditions during the last four years in a avocado plantation, an olive grove, a paulownia tree plantation and in selected urban sites. Savings of irrigation water in the range of 30 to 50 percent in comparison to irrigation amount using conventional practices were measured. Results from these field trials are presented and analyzed.

Introduction

The practice of water application for the irrigation of plants often results in the application of excessive amounts of water because of a number of reasons. First, the estimate of the amount of water to apply involves a number of errors. Second, the location of the depth of the bottom of the active root zone in real time is often a wild guess. Above all, a procedure to verify whether the amount of water applied is sufficient, deficient or excessive, is practically non existent.

Irrigation amount was traditionally estimated on the basis of direct soil water sampling. Presently, it is sometimes estimated using dedicated soil water sensors but mainly by estimating irrigation amounts based on the measurements of weather parameters related to water evaporation. Clearly, all methods involve significant errors often resulting in the application of excessive or deficient amounts of water.

We examine here the possibility of replacing the irrigation amount as an irrigation control parameter with the final depth of the redistribution front. The justification for this substitution is that the final depth of the redistribution front in a given soil profile is closely related to the amount of water applied during irrigation. At a first glance this alternative is impractical because the redistribution front reaches its stable depth hours or even days after irrigation is terminated. In addition, we presently lack the methodology to estimate in real time two closely related parameters, the final depth of the drainage following irrigation and the depth of the bottom of the active root zone.

The conceptual, technological and practical solution to the realization of this alternative is the heart of our irrigation control with feedback loops system and is the objective of this presentation.

Theory

Final depth of the redistribution front as an irrigation control parameter

The water balance of a soil profile, following wetting at its surface by rain or irrigation, involves three stages, the wetting stage, the redistribution and the drying stage.

During the wetting stage water reaching the soil surface moves downward in a piston like movement, wetting each layer to a maximal value before advancing to the next layer. Under conditions when the water is being applied to the soil surface at a constant rate, the rate of advance of the often visible wetting front moves down the soil profile at an essentially constant rate. The actual rate of advance depends on soil texture, initial soil water content and on the water application rate. The velocity of advance of the wetting front is normally in the range of 5 to 20 cm. per hour and the duration of wetting stage is in the range of fractions to full hours.

The redistribution stage starts when water application stops. It is characterized by two processes taking place at the same time. Soil layers above the final wetting front are gradually draining as a result of the downward movement of excess water in response to gravitational forces. Soil layers below the location of the final wetting front are being wetted up in response to the movement of the drainage water from the wetted soil depths. Both the rates of the drainage of the previously wetted soil layers as well as the rates of wetting of the deeper soil layers are gradually diminished.

The downward movement of the redistribution front below the final location of the wetting front is of special interest since it determines the final depth of the wetted soil profile following irrigation.

The redistribution front is identified as a soil layer, below the wetting front, where its soil water content gradually increases following cessation of irrigation. Its rate of downward advance decreases with time and reaches a practical stop at deeper soil layers. The final, stable, depth of the redistribution front is influenced by soil properties and by the location of the wetting front at the end of irrigation.

The stage of soil drying, as a result of water uptake by roots (or evaporative drying), takes place all the time. It becomes the major process responsible for changes in the soil water content along the soil profile, when the redistribution stage is reaching a relatively slow rate in comparison to the drying rate. The relative rate of soil drying is related to the rate of water loss by the canopy and to the density of roots in the soil layer.

The soil drying front is identified by a significant decrease in the water content of a soil layer. It was reported to move downward in field crops in parallel to the downward movement of new active roots. For fruit trees with a relatively stable root distribution, the rate of soil drying is closely related to the density of active roots and to climatic conditions.

Based on the above analysis, it is proposed to control the final depth of the redistribution front (the final depth of the wetted profile and thus the irrigation amount) by the selection of the correct depth of the wetting front to stop irrigation.

When to stop irrigation

A search for a depth of the wetting front to stop irrigation that would bring to a stop the drainage front at the known bottom of the active root zone.

It is assumed here that the final depth of the redistribution front, for a given soil profile, Z_F, depends mainly on the depth of the wetting front at the end of irrigation, Z_I, (which is function of the quantity of water applied). Initial attempts to develop a theoretical relationship between, Z_I, and, Z_F, were unsuccessful, especially when tested experimentally under realistic conditions. Clearly, the relationships between these two parameters is rather complex and is being influenced by a large number of factors that could not be quantified (soil texture, soil structure, profile uniformity, presence of less permeable soil layers etc.). Thus, the theoretical estimation of an optimal value of, Z_I, to stop irrigation, so that the resulting final depth of the redistribution front, Z_F, would reach the bottom of the active root zone in real time is not a realistic control objective.

The solution to this interesting problem was to develop a series of algorithms that would function as a question and answer learning system that could play a guessing game in order to find the correct value of Z_{Ii}. As a first step, the planned final depth of the redistribution front, Z_F, based on real time knowledge of the location of the bottom of the active root zone is established. Than, a first test value of Z_{Ii} is selected, irrigation is initiated and than stopped when the wetting front reaches the first test depth Z_{Ii}. The location of the redistribution front is tracked in real time until its final stable depth Z_{Fi}, is reached. A comparison is made between the planned and the measured values. If Z_{Fi} is deeper than Z_F, too much water was applied. Then, the next test wetting front depth to stop irrigation, Z_{Ii+1} will be shallower than the first one, less water to apply. If Z_{Fi} is shallower than Z_F , too little water, then the next wetting front test depth to stop irrigation would be deeper than the first test value.
These trial and error tests are repeated until the optimal value of Z_{Ii} is found (it takes two to three iterations). This learning process is repeated prior to each irrigation cycle.

When to start irrigation

The time to start irrigation determines the maximum value of water deficit developed in the crop. The relationships between the level of crop deficit and the various yield expressions are complex. Thus, it is presently quite difficult to time irrigation based on a specific measure of crop water deficit. In our present irrigation control system we take advantage of the detailed information concerning root activity as a function of soil depth (slope of water extraction by the sensors along the probe). Accordingly, we have developed a start irrigation algorithm where the soil layer-sensor depth-where maximum root activity takes place is an input to the system. A start irrigation command is issued when change in the sensor's reading, since the end of the drainage stage, is a predetermined percent value .The higher the percent the longer is the time to start next irrigation.

Logic of the control irrigation system with feedback

1. Input value of Z_F, planned final depth of redistribution front at bottom of active root zone.
2. Input value of Z_{RM}, depth of layer with maximum root activity.

3. Input value of threshold percent change in resistance value during drying stage of sensor at depth Z_{RM} since end of drainage stage to start irrigation

4. Input value of delta R, threshold percent change in resistance of sensor reading to identify arrival of wetting or drainage fronts.

5. Select first value of Z_{Ii}, depth of wetting front to stop irrigation.

6. Start first irrigation.

7. Scan sensors along depth probe every two minutes during wetting stage to track Z_{Ii} the location of the wetting front.

8. Scan probe until sensor Z_{Ii} is identified.

9. Stop irrigation.

10. Scan sensors below depth of wetting front every eight minutes for Z_{Fi}, redistribution front position.

11. Locate probe with Z_{Fi} actual final depth of redistribution front.

12. If depth of Z_{Fi} is larger than the planned final depth Z_F, excess irrigation, than next depth of wetting front to stop irrigation, Z_{Ii+1} would be shallower than Z_{Ii} . If Z_{Fi} is smaller than Z_F , deficient irrigation , than Z_{Ii+1} would be deeper than Z_{Ii} . If $Z_{Fi} = Z_F$ than $Z_{Ii+1} = Z_{Ii}$.

13. Scan resistance value of sensor at Z_{RM} , depth of maximal root activity.

14. If threshold value of resistance of sensor at Z_{RM} is reached than start irrigation.

This sequence is being repeated during each irrigation cycle

Experimental

A major requirement for the realization of this plan is the experimental ability to track the location of both the wetting front and the drainage front during an irrigation cycle. In addition, a procedure to obtain a measure of root activity as a function of soil depth must also be developed.

We have designed, constructed and field tested a depth probe capable of tracking the wetting and redistribution fronts as well as the rates of soil drying in real time. The depth probe, **Fig 1,** consists of a plastic cylindrical rod, 25mm outside diameter, on which metal rings, 10mm wide are imbedded at 50mm intervals. Each ring is connected by a conductive wire to a control box outside the probe. Each pair of rings makes up a sensor, the top of the first sensor is 4cm from the soil surface, the second at 10cm cm and top of the eights and last sensor is located 46cm from the soil surface. Using a dedicated circuit in the control box measures the electrical resistance between the adjacent pair of rings. When the depth probe is inserted into the soil, each sensor (adjacent pair of rings) measures the soil electrical impedance between the two rings. The soil electrical impedance is sensitive to its clay content, its water content, salt concentration in the soil solution and soil temperature. Clearly, we are not interested in an exact estimate of the water content of the surrounding soil. Rather, our interest is in the relative change in the impedance reading as a result of a relative change in the soil water content as a result of the arrival of the wetting front, the redistribution front as well as the soil drying as a result of water extraction by roots.

The sequence of data collection by the depth probe following irrigation is as follows:

Tracking the wetting front

Once a signal to start irrigation is outputted, the wetting stage stats. Because of the short time constant of the wetting process the sensors along the probe are scanned every two minutes and the system looks for a sudden five percent decrease in the impedance readings of each sensor indicating the arrival of the wetting front to the top of the sensor.
A realistic example of the tracking of the wetting front during the wetting stage – irrigation - is presented in **Figure 2.** A number of characteristics are apparent.
First, the movement of the wetting front is orderly layer after layer and practically at a constant velocity. The time it takes for the wetting front to advance through a sensor for this soil is about one hour. During that time the reading of the impedance decrease at a constant rate and once the front reaches the bottom of a sensor the impedance value remains constant until the end of the wetting stage.

Tracking the redistribution front

When a command to stop irrigation is outputted, the scanning system moves to the drainage of the sensors above the wetting front and then to the redistribution stage in the layers below the wetting front where the probe is being scanned every eight minutes.
A realistic example of impedance readings of the sensors for a 12 hour period during the wetting and for about eight hours after irrigation stopped is presented **in Figure 3.** The impedance reading of the sensors along the probe after irrigation stop could be divided into two groups. For sensors located above the location of the final depth of the wetting front, 22cm, their impedance gradually increase indicating soil drying as a result of drainage of excess water. For sensors located below the depth of 22cm,(lower graph) their impedance readings decrease with time indicating that the surrounding soil layers ate being wetted as a result of redistribution. The process of wetting of the lower soil layers continues for some times after irrigation stopped until it reaches a practical end. The final wetting depth during redistribution, Z_{li} , was 40cm. When Z_{Fi} is located, the system reaches the end of the redistribution stage and the start of the drying stage. This stage lasts until the beginning of the next irrigation. The main data collection at this stage is scanning of the sensor located at the depth of the maximal root activity to indicate the time the threshold increase in its

impedance was completed. Once this point is reached a signal to start irrigation is issued by the control box to the solenoid valve.

Examples of the type of data being collected by the sensors along the depth probe during a conventional, non controlled, irrigation cycle for a heavy soil irrigated with mini sprinkles are presented in Figure 4 and with drippers in Figure 5.
The time changes of the eight sensors along the depth probe inserted in an avocado plantation during an irrigation cycle every two days using mini sprinklers are presented in **Figure 4.** All eight sensors, down to a depth of 52cm, responded to the irrigation event. Following irrigation cessation a slight decrease in the impedance readings of all sensors, as a result of drainage of excess water from all soil layers can be observed. About six hours after irrigation stopped the impedance readings of the sensors started to increase as a result of a decrease in the soil water content of the adjacent soil layers. For the sensors down to the depth of 28 cm the drying of the soil layers was mainly a result of water uptake by the avocado root system. The slow increase in the impedance readings of sensors below the depth of 34cm is probably due mainly to continuous slow drainage of soil water to deeper layers.
Based on these results it is suggested that most of active root system of the avocado tree extended down to a depth of about 34m only. Clearly, this avocado plantation was irrigated in a considerable excess of water.
An additional important conclusion from present result is the maximal activity of the avocado root system was located at the 10 to 16 cm depths.

Result from a wetting depth probe, inserted in the soil of an adjacent avocado field daily irrigated by a drip system, are presented in **Figure 5.** Generally, the time changes in the impedance readings of the eight sensors along the probe are similar to those presented in Figure 4. All the eight sensors respond to the advance wetting front every day. Because of the daily application of water, the slight decrease in the impedance readings of the sensors is not apparent and the soil drying process begins almost immediately. The soil drying pattern of all sensors down to the depth of 34 cm appears to be the result of water uptake by the active root system of the avocado trees. The impedance readings of the deeper sensors continue a pattern of additional decrease in their impedance readings as a result of continuous wetting of the soil layers down to the depth of 52cm. No doubt the drip irrigated soil is receiving excessive amounts of irrigation water. Based on the impedance readings of the sensors, slope of the time changes, the bottom of the active root zone is at 34cm. as observed in the section irrigated with mini sprinklers. The soil layers with the most active roots are located at the soil depth range of 28 to 34cm, deeper than that under mini sprinkler irrigation.

Using the results of frequent scanning the sensors along the depth probe, both the depth of the bottom of the active root zone as well as the depth range inhabited by the most active roots was demonstrated using the field results presented in Figures 4 and 5.

Results and Discussion

The irrigation control system with feedback loops has been under field testing since 2004. Normally the tests were conducted in cooperation with the local farm advisers and the measured weekly and seasonal water use in the test plots were compared with measured values from neighboring plots irrigated using local best practices. The amounts of water used by the test control areas were taken from records accumulated in the irrigation computer controlling the irrigation of the whole plantation. Field trials were conducted in an avocado plantation on a clay soil in kibbutz Yechiam, Western Galilee, an olive grove on a sandy loess soil, in kibbutz Revivim Southern Negev and a Paulownia tree plantation, on a sandy loam soil, kibbutz Givat Haim, coastal plane. The test plots were under the control of a solenoid valve which was normally operated by a central irrigation computer. The test area varied from one to four hectares. The sensors along the depth probes were frequently scanned, depending on the stage of soil wetting, and the data was stored in the control box and downloaded once a week to a lap top, analyzed and plotted. The figures showing field results normally cover a period of about 7 days only, this in order to demonstrate as many details as possible of the events taking place in real time. .

Results from an avocado field irrigated with mini sprinkles under our irrigation control with feedback system during October 2005, are presented **Figure 6.**
On the upper part of each figure are the time and duration of irrigation. Also in each parenthesis, the left number represents the sensor number located at the planned final wetting depth, Z_{Fi} , and the right figure represents the selected sensor number that will stop irrigation when detecting the arrival of the wetting front , Z_{Ii}. During the present test the planned final depth of wetting was at sensor number 5 – 34cm. The sensor number to stop irrigation was changing between 3 and 4 representing stopping depth of 22 and 28 cm. The lower figure highlights the behavior of the deeper sensors- soil layers.

At the end of first irrigation the impedance readings of sensor 5 indicate that the surrounding soil was not wetted by the redistribution front, see lower figure. The feedback system reacted and the sensor to stop irrigation changed to a deeper one, number 4. The immediate result was an increase in the duration of irrigation from 2.35 hours to 2.49 hours and the sensor at the planned final wetting depth indicated the redistribution front reached it, a significant decrease of its impedance reading. The wetting of sensor 5 was excessive and as a result the stopping sensor for next irrigation the sensor to stop irrigation was changed back to number 3 and the duration of next irrigation dropped accordingly.. This feedback control pattern repeated itself a number of times. The end result, see lower figure, is that the impedance readings of the deeper sensors at the 40 and 46 cm depths were

practically constant, with changes less then five percent in their value. This stability is the result of the feedback loop system and indicates that the leakage of soil water to deeper soil layers as a result of the application of excessive amounts of water was avoided. The percent saving of the measured water amounts applied under the irrigation control with feedback system compared to the measured water amounts applied to adjacent area irrigated using recommended practices was 35 percents.

The time changes in the sensor readings along the depth probe in a test area planted with olives and irrigated with drippers are presented in **Figure 7**. The solenoid valve of this area was under the control of our irrigation control with feedback system. The period presented in this Figure was that of 6 days at the end of October 2005. The planned final wetting depth was at sensor number 4 – 28cm and the sensor to stop irrigation was at sensor number 3 – 22cm. throughout the reported test period. The control system resulted in irrigation every two days during the test period.

The impedance reading of the sensor at 28cm, final wetting depth, and of the sensor at 34cm were practically stable with a slight tendency to dry. Under this situation the feedback control system did not see any reason to change the depth of the sensor that stops irrigation. The impedance readings of the sensors at 40cm and 46cm depths, see lower figure, were practically stable. Thus, no drainage of excess irrigation water was detected. The percent of saving of the measured water amounts in the test area under the control of the irrigation control with feedback loops during the test period was 42 percent compared to that measured in an adjacent area that was irrigated according to the best practices recommended by irrigation extension personnel.

Figure 8 presents the time changes in the impedance readings of sensors along a wetting depth probe inserted in a Paulownia tree plantation on a sandy loam soil during the first part of May 2007. The trees were irrigated with a drip system and irrigation was managed by the irrigation control with a feedback loop. Irrigation was initiated by the system every 4 days. The planned final wetting depth was by sensor number 4 at a depth of 28cm. The sensor to stop irrigation was changed by the control system between numbers 2 and 1 equivalent to depths of 10 and 16 cm.

During the first irrigation water application was stopped when sensor number 2 detected the arrival of the wetting front, irrigation lasted for one hour. The impedance reading of sensor number 4 dropped slightly as a result of the arrival of the redistribution front. Thus, next irrigation, the sensor to stop irrigation changed to a shallower soil depth, number 1. The result was that sensor 4 hardly sensed any change in its impedance and a fast correction to sensor number 2 was made and an additional irrigation followed. The total duration of water application was 75 minute. The impedance reading of sensor 4 decreased somewhat. For the next irrigation the feedback loop system changed the sensor to stop irrigation to the sensor at 10 cm. number 1. The duration of irrigation was 36 minutes and the impedance reading of the planned last stopping depth, sensor number 4, did not change.

The impedance readings of sensors at 40 and 46 cm along the depth probe hardly changed during the eight day test period indicating that the amounts of water applied were just enough to wet the planned last wetting depth. The percent saving of the measured irrigation amounts during the month of May by the test area compared to the irrigation amounts applied to the neighboring areas irrigated following the practices recommended by the local extension service was 47 percent.

Summary and Conclusions

The concept of using the planned final depth of the redistribution front following irrigation as a control objective was introduced and the difficulties discussed. Relationship between the location of the wetting front at the end of irrigation and the final depth of the redistribution front at the end of an irrigation cycle were analyzed. A set of algorithms forming a learning trial and error system was developed in order to select an optimal depth of the wetting front to stop irrigation. This choice should result in a final location of the redistribution front at the depth of the bottom of the active root zone.

Accordingly, sensors, equally spaced along a depth probe, capable of tracking the locations of the wetting front during irrigation and the locations of the redistribution front following irrigation were designed constructed and tested. In addition, a logical sequence of algorithms for the control with feedback of irrigation was developed.

The combination of a wetting depth probe and a control box was tested under realistic conditions. We have demonstrated the ability of the sensors along the probe to track in real time the position of the wetting front during irrigation and the location of the redistribution front following the end of irrigation. In addition, we have shown that by daily scanning of the sensors along a probe inserted in an irrigated soil with a growing crop, it is possible to locate the location of the bottom of the active root zone as well as the depths where the activity of the root system is at its maximal rate.

In Figures 4 and 5, measurements of the time changes of sensors placed along depth probes inserted in locations in an avocado plantation irrigated by mini sprinklers (fig.4) and irrigated by drippers (fig.5) during an irrigation cycle. The results demonstrate the ability of the data logging system to analyze the distribution of the active root system based on its ability to extract soil water as a function of soil depth. Also, the sufficiency of the application of irrigation amounts could be independently analyzed.

The time changes of the measured impedance readings of sensors along depth probes inserted in plots irrigated under the control of the irrigation control with feedback system were presented in Figure 6, avocado irrigated with mini sprinklers, in Figure 7, olive grove irrigated with drippers and in Figure 8, Paolownia tree plantation irrigated by drippers. In all presented field examples the effectiveness of the irrigation control with feedback system was apparent. First, in establishing a effective maximal final wetting depth at the bottom of the active root system. This final wetting depth was maintained using the feedback loops by controlling the time, and thus the amount, to stop irrigation by the control of the optimal depth of the wetting front to stop irrigation. In all examples the depth of the sensor to stop irrigation was changed when needed in response to whether the redistribution front arrived or passed the planned final depth of wetting. As expected the induced changes in the depth of the location of the sensor to stop irrigation immediately affected the duration of the water application.

The results in all the field tests of the activity of the irrigation control with feedback system were:

1. The water content of the soil layers below the planned final wetting depth remained unchanged indicating that no excessive amounts of irrigation water were applied.
2. Substantial saving of irrigation water was achieved as a result of the application of our control system, 35% under the avocado plantation, 42% under the olive grove and 45% under the Paolownia tree plantation.
3. The danger of leaching of soluble salts to the water table as a result of the application of excessive amounts of irrigation water was minimized.
4. No damage to the test plants was apparent as a result of applying the irrigation control with feedback system

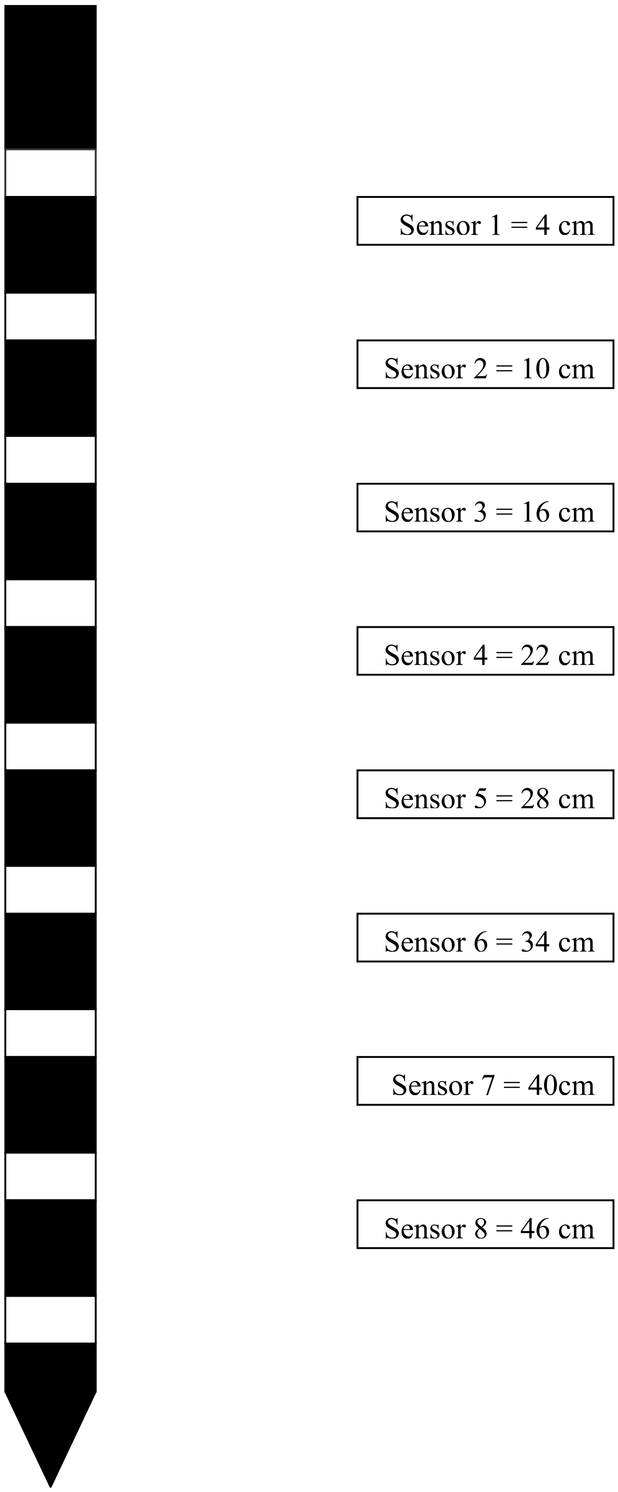


Fig. 1 – Wetting fronts depth probe

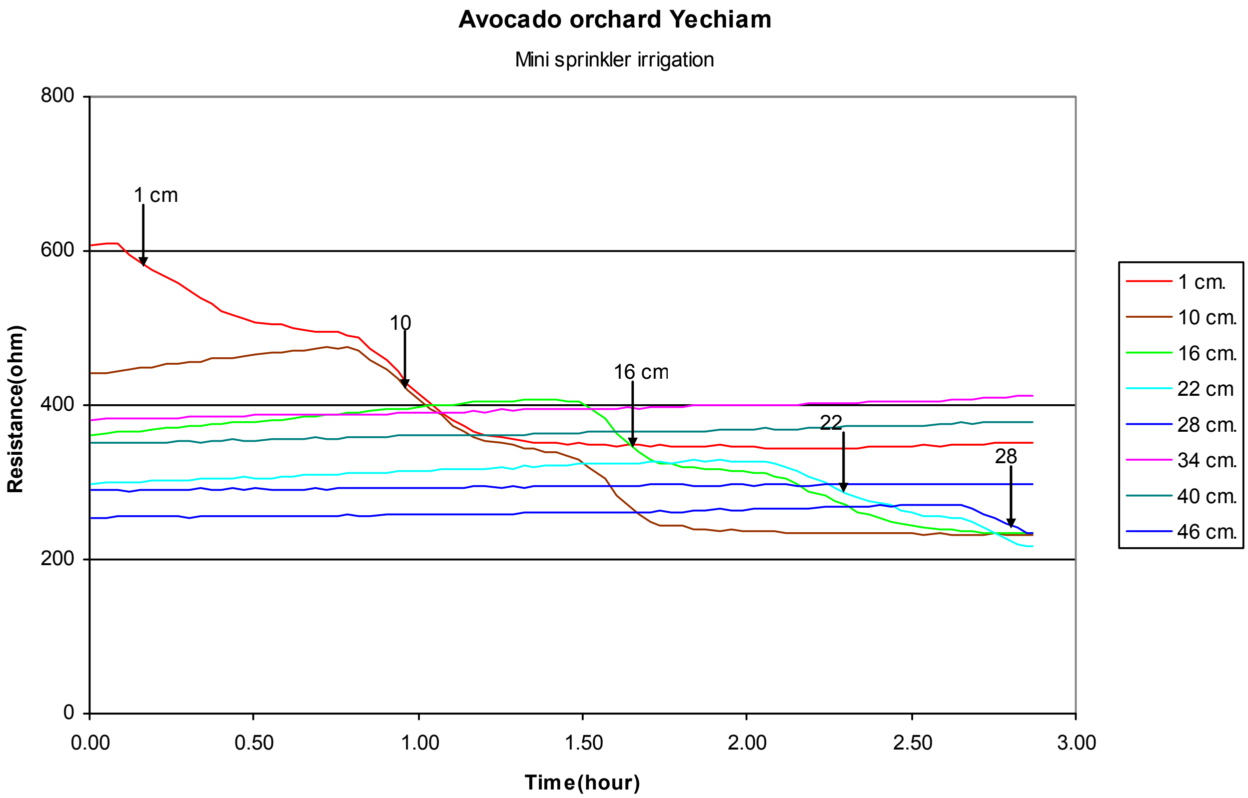


Fig. 2 – Tracking the position of the wetting front, field results.

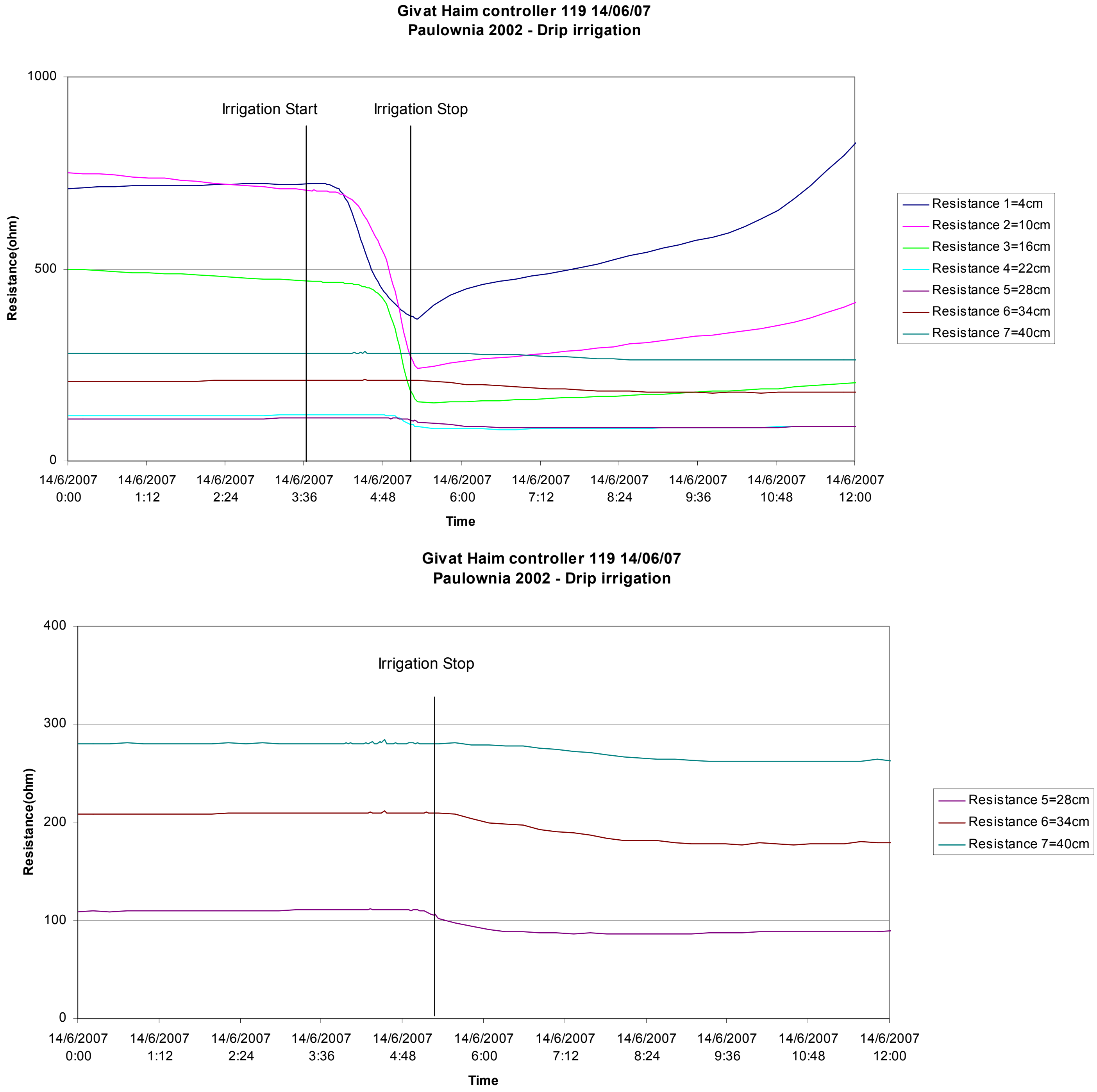
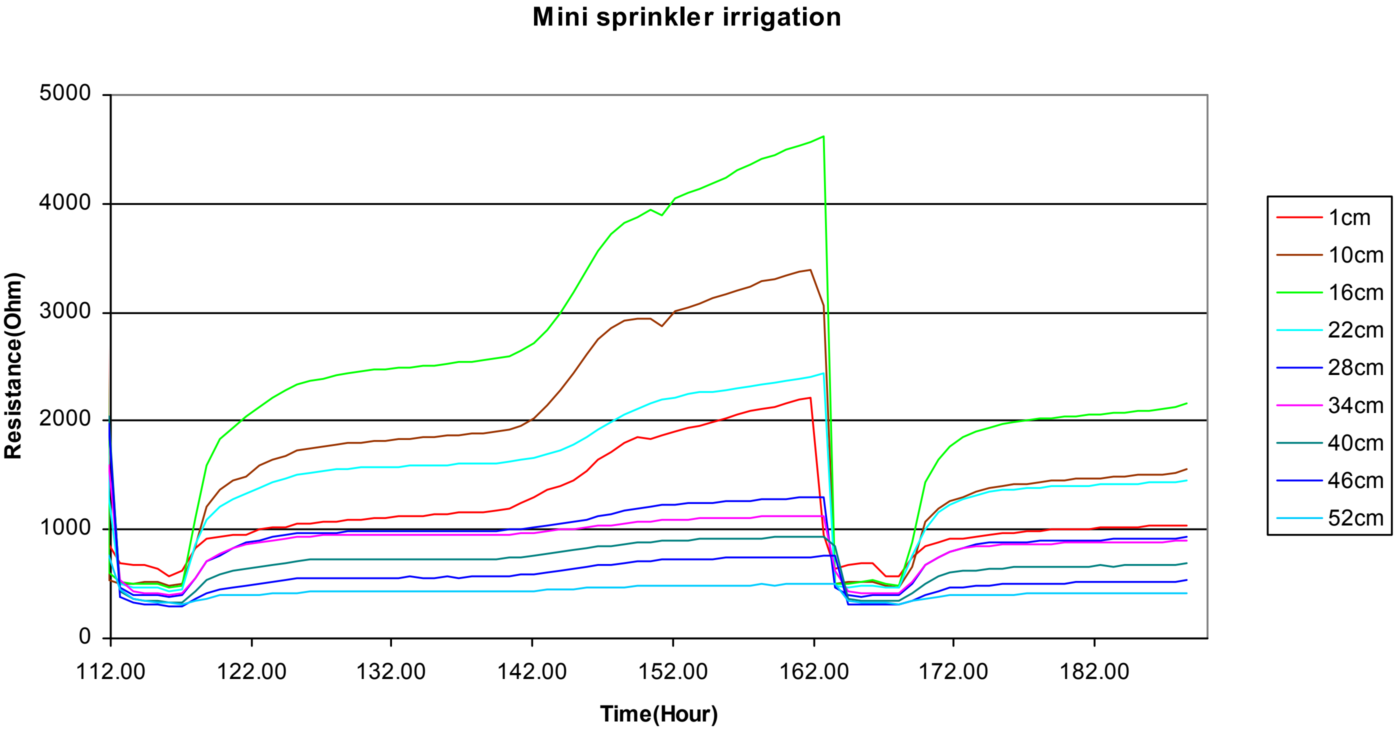


Fig. 3 – Tracking the drainage and redistribution fronts, field results.



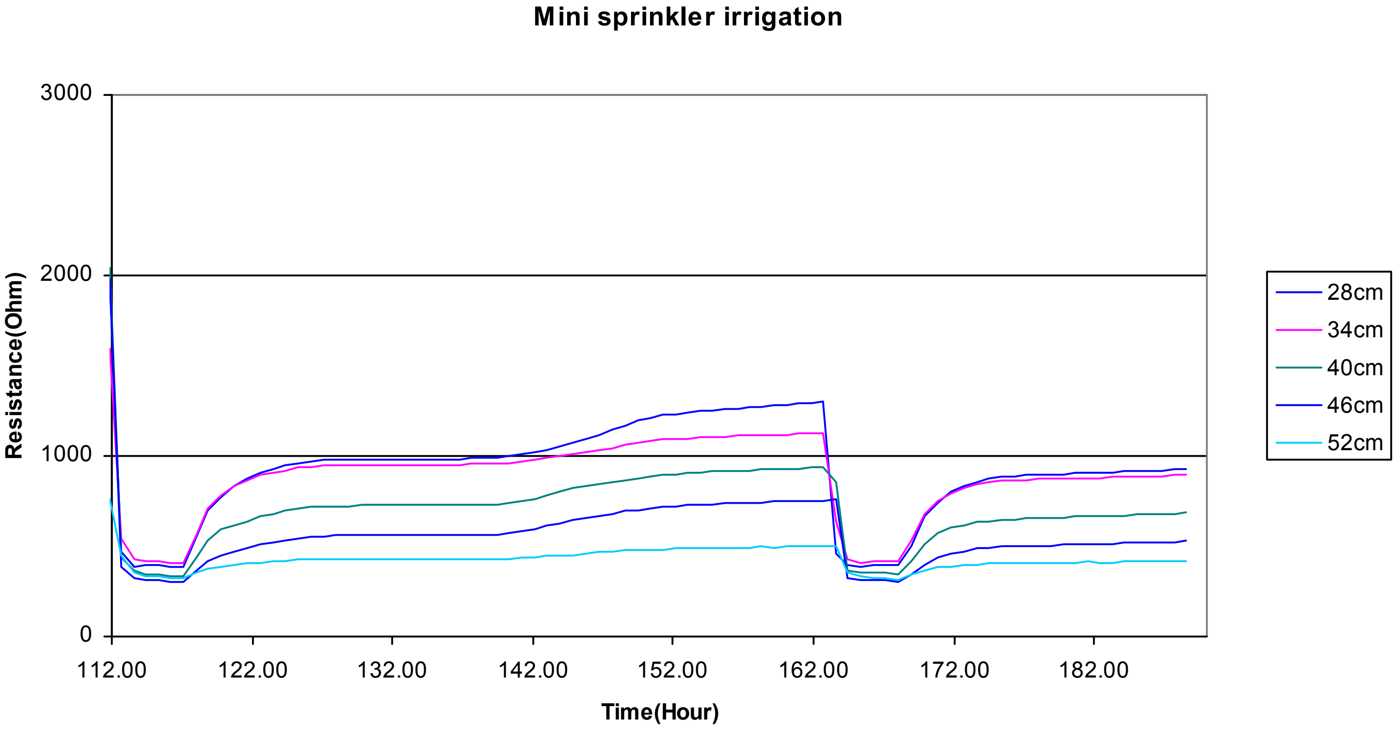


Fig. 4 – Time changes of the impedance by sensors along the probe.
Avocado, mini sprinkles, no control

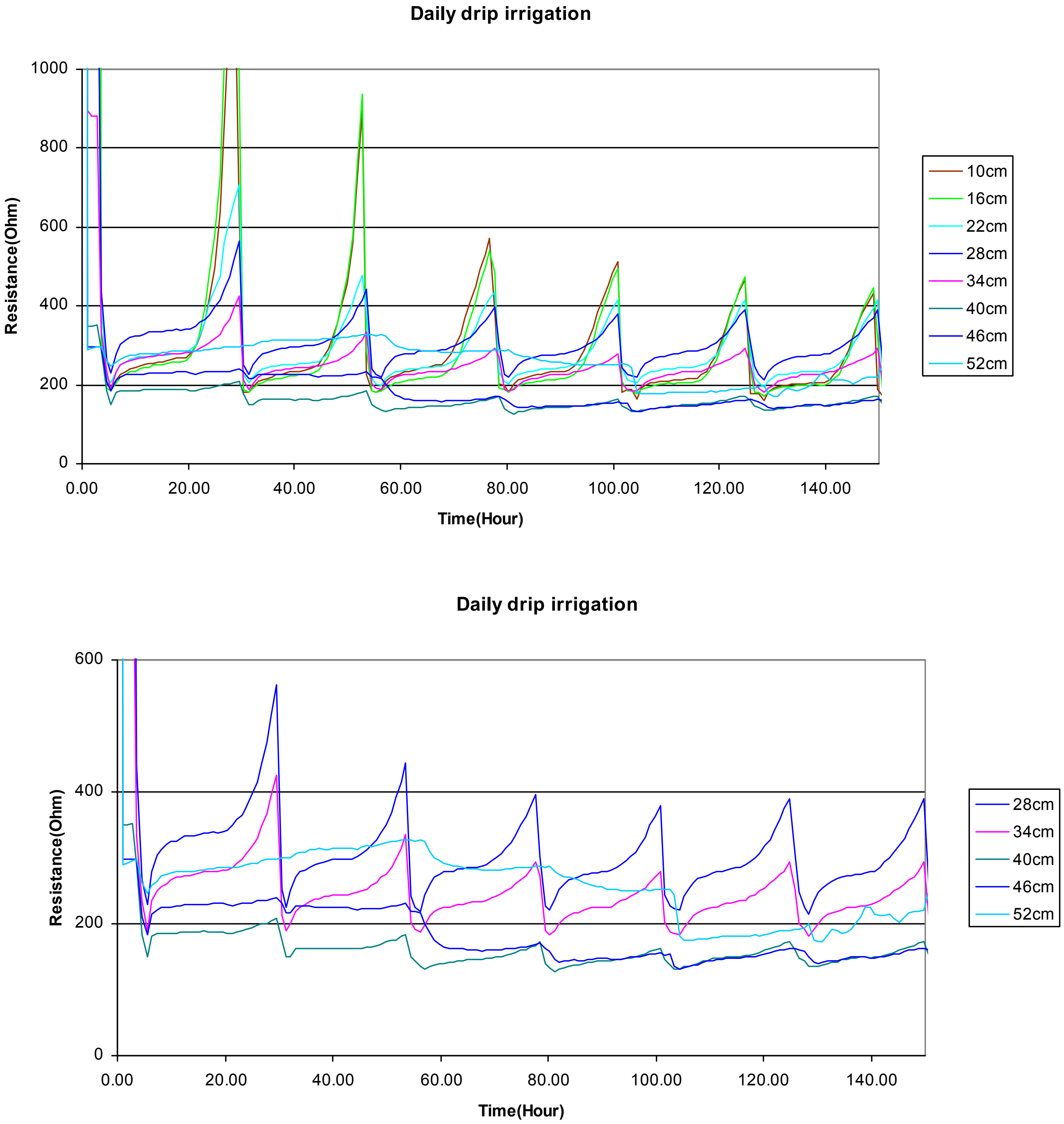


Fig. 5 – Time changes of the impedance by sensors along the probe.
Avocado, drippers, no control

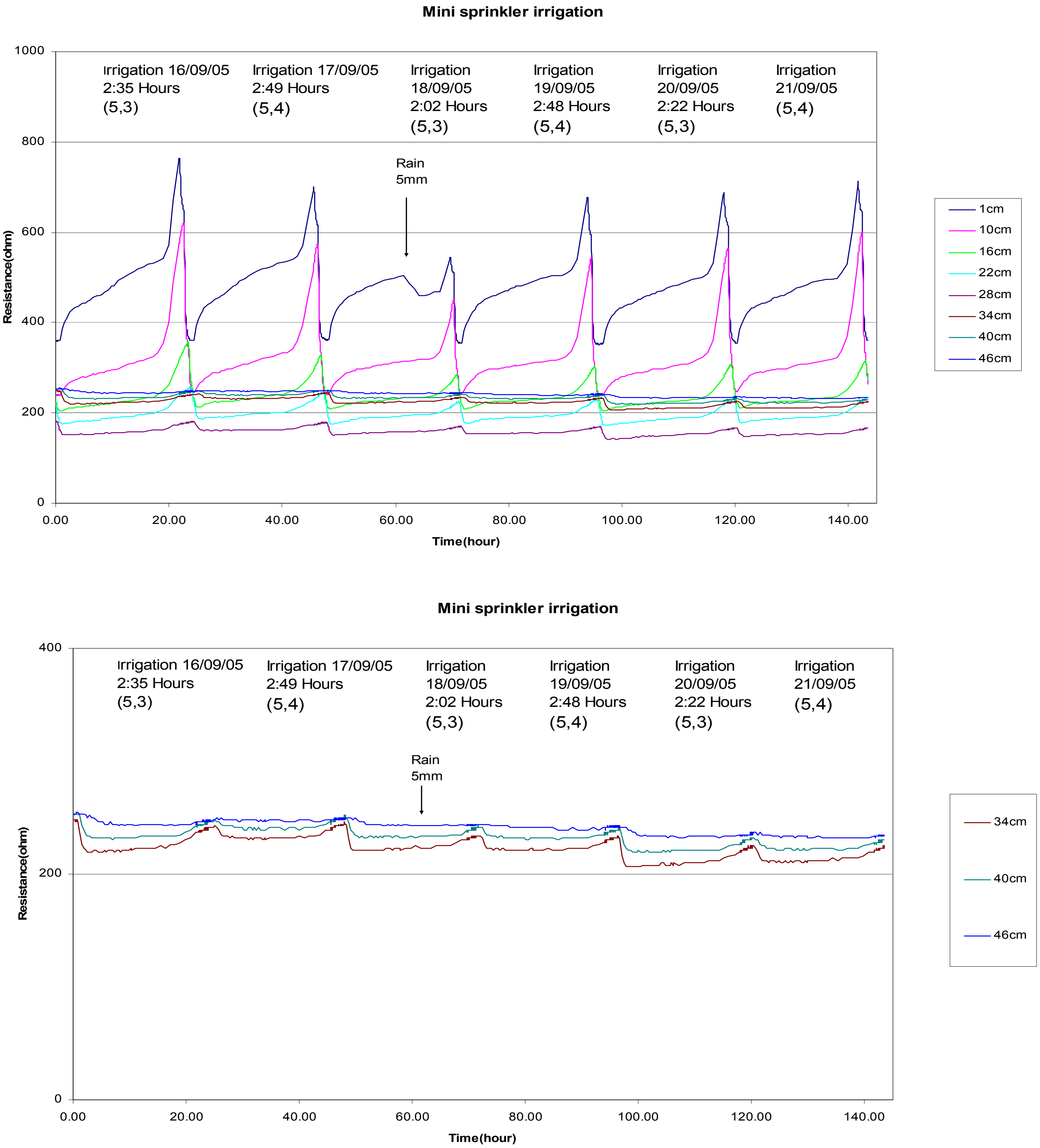
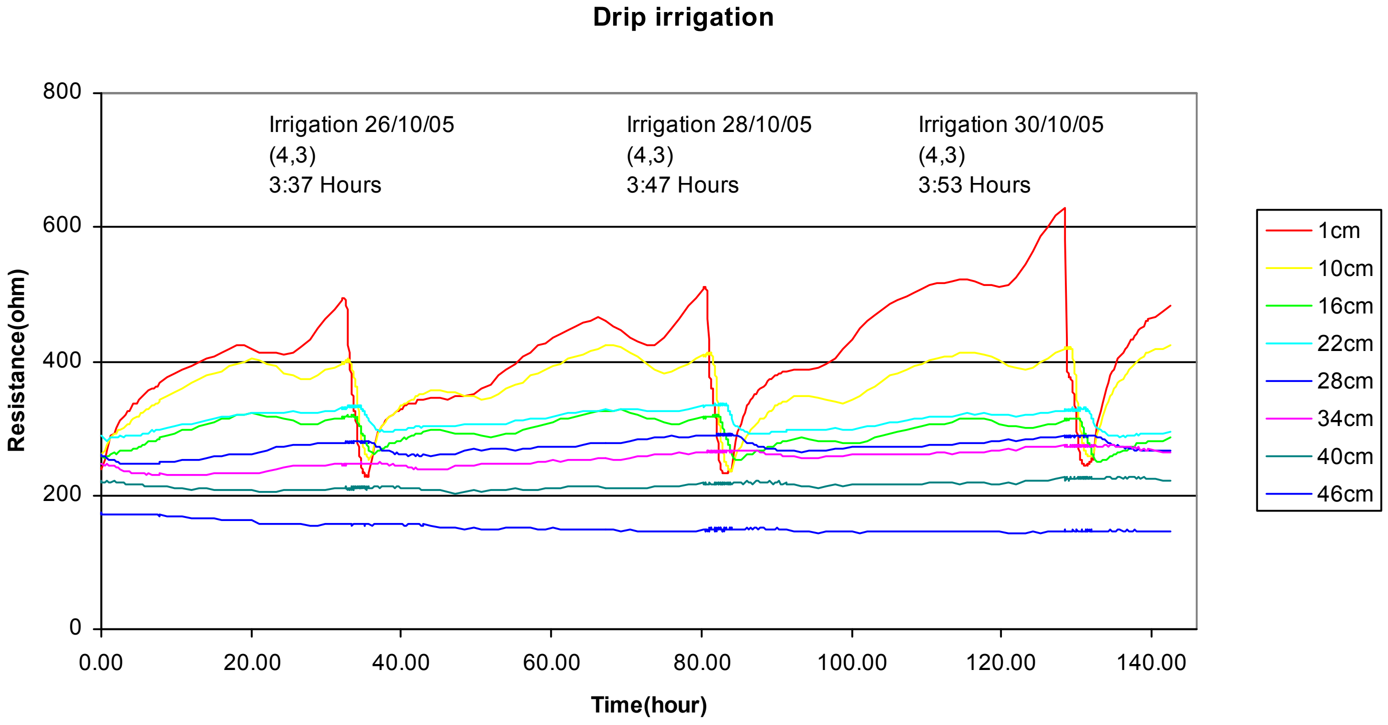


Fig. 6 – Time changes of the impedance by sensors along the probe. Avocado, mini sprinklers, irrigation control with feedback.



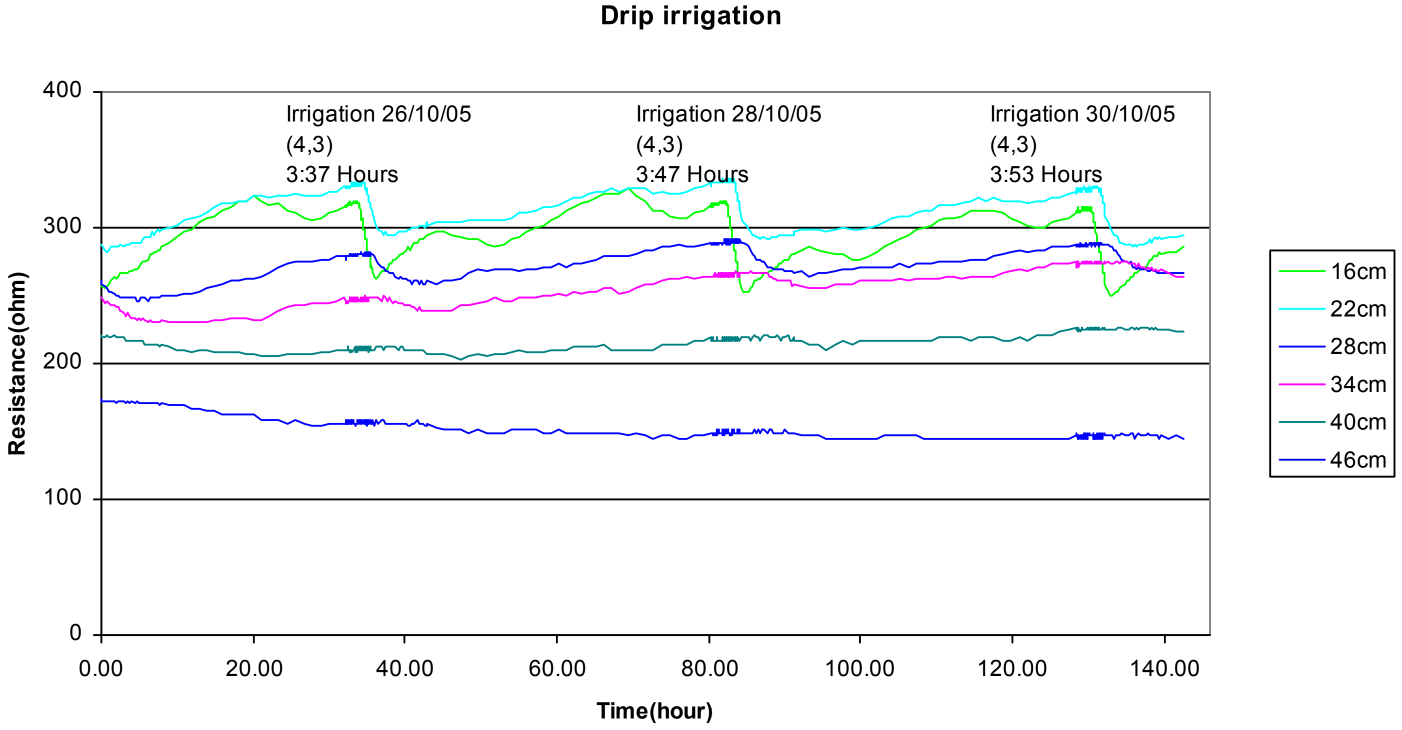


Fig. 7 – Time changes of the impedance by sensors along the probe.
Olive grove, drippers, irrigation control with feedback.

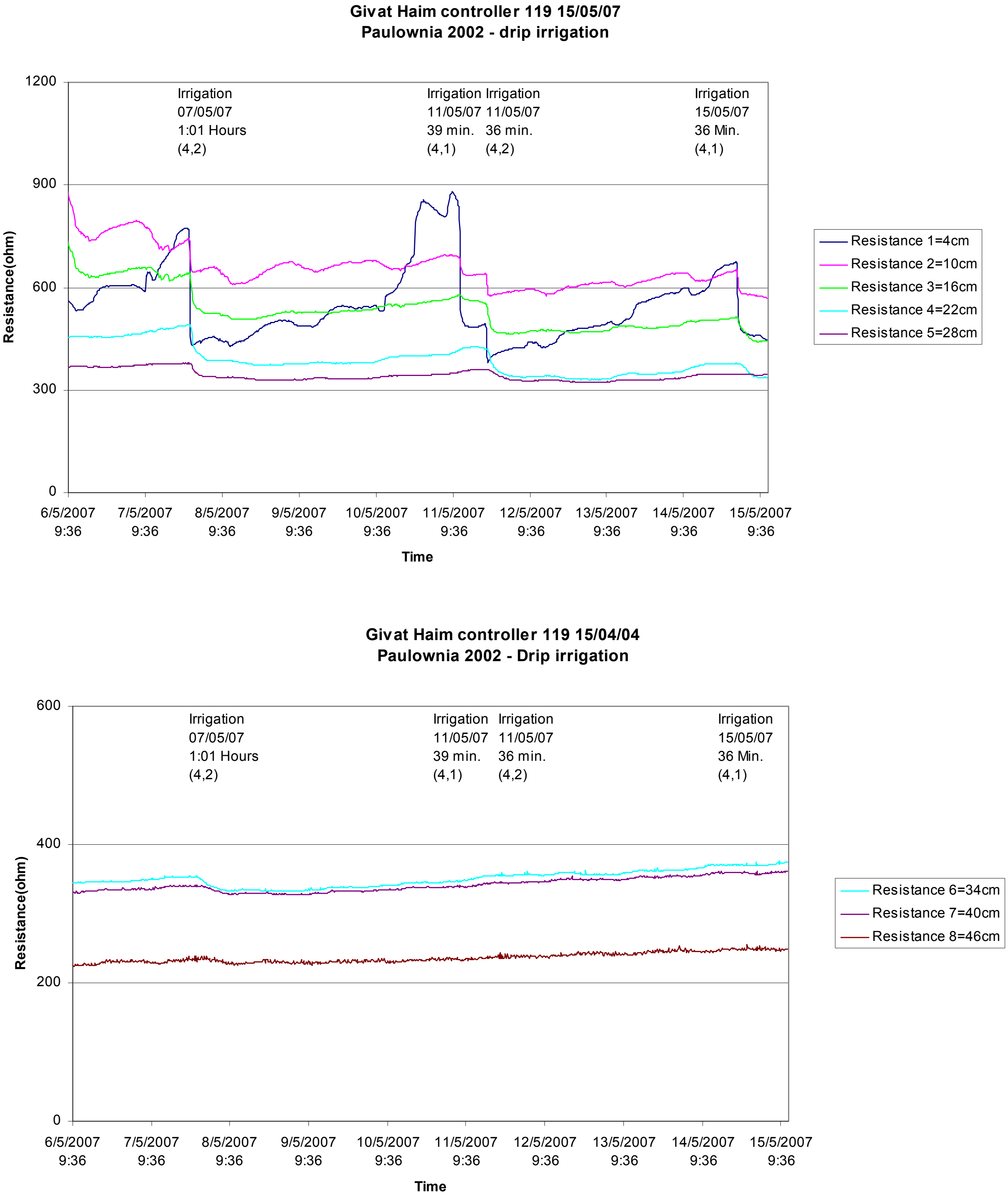


Fig. 8 – Time changes of the impedance by sensors along the probe.
Paulownia Tree Plantation, drippers, Irrigation control with feedback

Irrigation Association Smart Water Application Technologies (SWAT) scores and water conservation potential

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Abstract. *The Irrigation Association (IA) Smart Water Application Technologies (SWAT) program was developed to test irrigation controllers to ensure they are able to respond to climate demand or to other feedback from the irrigated system such as soil moisture. Irrigation controllers are tested to gauge their response to climate factors and or soil moisture relative to conventional irrigation theory. Although the SWAT testing process serves as a benchmark to ensure that controllers can respond to changes in climatic or soil moisture conditions, an assessment has not been performed linking SWAT testing controllers to water conservation potential. The objectives of this study were to compare SWAT scores of irrigation adequacy and scheduling efficiency to water conservation potential of controllers tested under field conditions. It was found that generally, irrigation scheduling efficiency decreased as rainfall increased and the irrigation adequacy increased. High scores were not absolutely necessary to guarantee good turf quality. In addition, high scores did not guarantee high levels of water conservation. Thus, the SWAT protocol testing does screen controllers for their ability to adjust relative to irrigated landscape conditions; however, it does not guarantee water conservation.*

Keywords: scheduling efficiency, irrigation adequacy, SWAT, smart water application technology, water conservation.

1. Introduction

The development of Smart Water Application Technologies (SWAT) was initiated in 2002 by water purveyors who wanted to improve residential irrigation water scheduling. Later in 2005, studies reported in the California Water Plan Update, indicated water savings of 17% through the adoption of controllers automatically adjusted to reflect daily changes in ET (Huck and Zoldoske, 2006). SWAT is a national initiative coordinated through the Irrigation Association to achieve exceptional landscape water use efficiency through the application of irrigation technology. The SWAT protocol provides a procedure to evaluate the efficacy of irrigation system controllers that use either climatological or soil moisture data as a basis for scheduling irrigations. This evaluation is accomplished by creating a virtual landscape subjected to representative environments (zones) to evaluate the ability of individual controllers to adequately and efficiently irrigate that landscape. A soil moisture balance is performed by each zone as a standard procedure to test the controller's performance, and deficit and surplus for each zone calculated. The total accumulated deficit over time is a measure of the adequacy. Irrigation adequacy represents how well irrigation met the needs of the plant material. It has been suggested that if this value is above 80%, acceptable vegetation quality will be maintained (SWAT, 2008). On the other hand, the accumulated surplus of applied water over time is a measure of the scheduling efficiency. Although not clearly defined, it has been suggested that a scheduling efficiency score of at least 95% be required for controllers to ensure irrigation is efficient.

1.1 Irrigation controllers

Smart controllers measure depletion of available plant soil moisture in order to operate an irrigation system, replenishing water as needed while minimizing excess water use (IA, 2007). They also must recognize rainfall and its water contribution to the root zone in the irrigation schedule (Huck and Zoldoske, 2006). Examples of the various types of controllers include: historic ET, which uses historical ETo data from a table stored in the controller; on-site sensor, which uses one or more sensors to calculate ETo using and approximate method; real-time ET (real-time ETo is transmitted to the controller daily and it is usually determined using a form of the Penman equation); on-site weather station (central control), which is a controller or a computer connected to an on-site weather station equipped with sensors that record most of the parameters for use in calculating ETo with a form of the Penman equation (IA, 2007); controllers that use rainfall and temperature sensors; and soil moisture sensors, that can provide closed-loop feedback to time-based system controller, allowing controllers to recognize soil moisture levels and terminate irrigation events when soil moisture reaches predetermined levels (Huck and Zoldoske, 2006).

1.2 Testing of controllers for water conservation

Proper installation and programming of each of the technologies is essential element to balancing water conservation and acceptable turf quality (McCready et al., 2009). Evapotranspiration-based (ET) irrigation controllers that are designed to irrigate based on calculated ET needs of the crop. Results of a study evaluating three brands of ET controllers in residential landscaped plots compared to a homeowner irrigation schedule showed consistent water savings with two of the brands (from 14% to 40%). The treatments of this study, carried out in Florida, did not result in turf quality below acceptable levels (Davis et al., 2009). Another study carried out in Florida showed water savings between 25% and 62% when testing two brands of ET controllers on irrigated St. Augustinegrass (McCready et al., 2009).

Rain sensor (RS) controllers are small devices wired to the irrigation system controller designed to interrupt time clock scheduled irrigation cycles after a certain amount of rainfall occurs, conserving water while preventing irrigation (Dukes and Haman, 2002a). A study comparing bermudagrass plots under a completely time-based scheduling system with and without a rain sensor showed that the treatment without-rain-sensor used 45% more water than the with-rain-sensor treatment (Cardenas-Lailhacar et al., 2005). Another study testing rain sensors showed water savings of 7% to 30% when using rain sensor systems compared to historical net irrigation requirement, under dry to normal rainfall conditions, without reducing turf quality below acceptable limits (McCready et al., 2009).

Soil moisture sensor (SMS) irrigation controllers are designed to allow or bypass timed irrigation events (Dukes, 2005), providing a maximum water use efficiency by maintaining soil moisture at optimum levels (Cardenas-Lailhacar et al., 2005). Soil moisture sensor based irrigation control may offer some advantages over the climate based control technology. There are just few studies testing these SMS controllers. One is a study using soil moisture sensors to control residential irrigation systems in Colorado resulted in water saving of 27% compared to the theoretical water requirement calculated by a water balance (Qualls et al., 2001). Another study was carried out under Florida conditions during two 5-month periods, one in 2004 and the other in 2005, were three commercially available SMS controllers were tested on bermudagrass (*Cynodon dactylon* L.; Cardenas-Lailhacar et al., 2008). They reported water savings ranging from 69% to 92% during normal to rainy conditions for three of four controllers tested. Results for the 5-month period in 2004 only showed irrigation water saving from 46% to 88%. The turf quality was not affected, mainly because bermudagrass is known as a more drought-tolerant grass compared to other species (Cardenas-Lailhacar et al., 2005).Water savings were also reported by McCready et al. (2009) when using SMS controllers on St. Augustinegrass (*Stenotaphrum secundatum* (Walter) Kuntze) irrigation plots during dry conditions in Florida. Water savings ranged from 11% to 53% compared to a time based irrigation schedule developed based on the historical net irrigation requirement, and turf quality was above the acceptable limits.

The California Department of Water Resources funded two large programs in southern and northern California to improve urban irrigation efficiency and reduce runoff thorough the installation of smart controllers (Mayer et al., 2009). This study compared a single year of pre-installation data against a single year of post-installation data. The impact of 3,112 smart controllers installed at 2,294 sites at both sides showed that overall, outdoor water use was reduced by an average of 47.3 kgal per site (-6.1% of average outdoor use), a statistically significant reduction at the 95% confidence level. Seven of eight controller brands included in the analysis saved water on average; however the water savings associated with brand was not statistically significant. In addition, seven of the eight controller brands included in this study have published SWAT test results and all of the published SWAT scores were above 95% for adequacy. According to these results, it seems that the SWAT testing protocol may be used to predict a reasonable field performance, but not guarantee water savings.

The objective of this study was to compare SWAT scores of irrigation adequacy and scheduling efficiency to water conservation potential of controllers tested under field conditions.

2. Materials and Methods

2.1 Site description

The study was performed at the Plant Science Research and Education Unit in Citra, Florida. There were four treatment periods: 22 April 2006 to 30 June 2006 (S06), 23 September 2006 to 15 December 2006 (F06), 1 May 2007 to 31 August 2007 (S07) and 1 September 2007 to 30 November 2007 (F07). As described in McCready et al., (2009), the experimental area consisted of 72 plots (18.2 m^2 each) of 'Floratam' St. Augustinegrass (*Stenotaphrum secundatum*). Four Toro 570 Series (The Toro Company, Bloomington, MN.) quarter circle pop-up spray heads with a measured application rate of 50 mm h^{-1} irrigated the plots. Irrigation time clocks were used for scheduling all of the treatments except where a time-based controller was not necessary. Plot maintenance was according to local recommendations to maintain good quality during the growing season. Full details of the site layout and experimental procedures can be found at Shedd (2008) and McCready et al. (2009).

2.2 Data collection

Irrigation water applied was monitored using flow meters on each plot as described by McCready et al. (2009). Weather data parameters (rainfall, incoming solar radiation, relative humidity, air temperature and wind speed) were collected from an automated weather station (Campbell Scientific, Logan, UT) within 900 m of the experimental site (McCready et al., 2009). The ASCE standardized method (Allen et al., 2005) was used to calculate ETo. Monthly values of locally determined Kc were specified for a warm season turfgrass (Jia et al., 2009).

2.3 Experimental design

Table 1 shows all the experimental treatments evaluated for this study. A commercially available soil moisture sensor controller, Acclima Digital TDT RS500 (Acclima Inc., Meridian, ID.) was tested. Two different volumetric moisture content (VWC) thresholds were used in the testing, 7% and 10%. The soil moisture sensor (SMS) treatments had a sensor buried in the experimental plots to control irrigation. ET controllers included the Toro Intelli-Sense (The Toro Company, Bloomington, MN.) The Toro Intelli-Sense controller (TORO) calculates irrigation runtime and the frequency of irrigation events. Rain sensor (RS) treatments, using the Mini-Click rain sensor

(Hunter Industries Inc., San Marcos, CA), were set at several day of the week frequencies and threshold depths: 1 d/wk, 6 mm threshold; 2 d/wk, 6 mm threshold; and 7 d/wk, 3 mm threshold. There were two comparison treatments: a time-based treatment without a rain sensor (WOS) and a time based treatment with a rain sensor set at 6 mm and an irrigation depth equal to 60% of the possible depth scheduled for WOS and the other RS treatments (DWRS).

The same total application depth per week was divided over the possible number of irrigation days per week. Every treatment except for the TORO and the DWRS had the same possible total depth or irrigation application. The monthly irrigation schedule was based on local recommendations (Dukes and Haman, 2002b). Turfgrass quality evaluations were made using the National Turfgrass Evaluation Program (NTEP) procedures (Shearman and Morris, 1998), with details provided by McCready et al. (2009).

Table 1: Summary of irrigation controllers experimental treatment codes and descriptions (after McCready, 2009).

Treatment code	**Irrigation frequency (d/wk)**	**Treatment description**
Soil moisture sensor controller		
AC7	2	Acclima set at 7% VWC[1]
AC10	2	Acclima set at 10% VWC
ET controller		
TORO	2	Toro Intelli-Sense
Rain sensors and time-based irrigation		
RS1-6mm	1	Rain sensor set at 6 mm rainfall threshold
RS2-6mm	2	Rain sensor set at 6 mm rainfall threshold
RS7-3mm	7	Rain sensor set at 3 mm rainfall threshold
DWRS	2	Reduced irrigation schedule (60% of RS2-6 mm)

[1] VWC= volumetric water content.

2.4 SWAT 'inspired' water balance approach

A daily soil water balance (Dukes, 2007) was performed for the 2006 and 2007 testing periods. The actual water applied was input into this daily soil water balance along with ET and rainfall to determine the daily soil water level. These theoretical values were compared to the irrigation applied with the SMS, RS and ET systems in order to determine the irrigation adequacy and scheduling efficiency of water application. Direct runoff and soak runoff were neglected since they are not relevant due to the sandy soils with high infiltration rates. These two parameters are included, however, in the SWAT protocol (SWAT, 2008). The soil water balance equation was represented as follows:

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c,i} + DP_i$$

where $D_{r,i}$ is depletion of water from the root zone at the end of the day (mm), $D_{r,i-1}$ is depletion of water from the root zone at the end of the previous day (mm), P_i is precipitation (mm), RO_i is runoff from the soil surface (mm), I_i is irrigation depth applied (mm), CR_i is capillary rise from the groundwater table (mm), $ET_{c,i}$ is crop evapotranspiration (mm) and DP_i is deep percolation (mm). For this study, RO and CR were considered negligible due to the low slope inclination of the experimental site, the depth of the water table (more than 5 m deep) and the sandy soil texture. Any water applied in excess of field capacity is considered to contribute to DP. A root zone depth of 30 cm was used since this is the most frequent root depth found for warm-season grasses (Doss et al., 1960; Peacock and Dudeck, 1985). ET_c was calculated by multiplying ET_o (ASCE standardized method, Allen et al., 2005) and monthly K_c values specified for warm-season turfgrasses (Jia et al., 2009). The irrigation schedule used for the RS and SMS treatments was based on a system efficiency of 60%, whereas 95% efficiency was used for the TORO controller. Thus calculated gross irrigation was determined from these efficiency values. The depth of available water (AW) was calculated using the following equation (Cassel and Nielsen, 1986):

$$AW = \frac{(FC - PWP)}{100} * RZ$$

where FC is field capacity (cm^3 of water per cm^3 of soil), PWP is permanent wilting point (cm^3 of water per cm^3 of soil), RZ is root zone depth (mm). The depth of RAW is calculated using the following equation (IA, 2005):

$$RAW = MAD * AW$$

A MAD (maximum allowed depletion) factor of 50% established for turfgrass has been suggested by Allen et al., 1998. To account for the decrease in crop transpiration when the soil moisture was below MAD, the adjusted $ET_{c,adj.)}$ was calculated using a water stress coefficient (Ks) as described in Allen et al. (1998).

Irrigation adequacy (%) refers to whether or not the irrigation applied is sufficient for plant needs (SWAT, 2008) and was calculated as follows:

$$Irrig. adequacy = \left[\frac{ETc, adj - Deficit}{ETc, adj}\right] * 100$$

where deficit was calculated as the water that was needed by the plant and was not readily available. Scheduling efficiency is a measure of how well irrigation depths were applied while preventing runoff and deep percolation and was calculated using the following equation (SWAT, 2009):

$$Scheduling\ efficiency = \left[\frac{Net\ irrig. - Irrig. losses}{Net\ irrig.}\right] * 100$$

where irrigation losses (mm) are the amount of water applied that exceeded the FC of the soil, leading to runoff or deep percolation. Since runoff was assumed to be zero under this condition, any over irrigation was assumed to lead to drainage below the root zone.

Both scores (irrigation adequacy and scheduling efficiency) were calculated for running totals of 30-day periods. These scores were only calculated if rainfall totaled at least 10.2 mm and ETo was at least 63.5 mm during the testing period to be considered a valid value (SWAT, 2008). Water savings were calculated between each controller treatment water use and the WOS (without a sensor) schedule, that was as a baseline for comparison purposes.

3. Results and discussion

3.1 Adequacy scores versus water savings

Considering all controller treatments, there was no correlation between water savings and irrigation adequacy scores (R=0.0979) (Figure 1, Table 2). There was not a clear correlation between increased water savings and higher scores since there are high scores associated with low water savings. When analyzing by individual controller treatments, correlations showed positive higher values, reaching maximum R values for AC7 (R = 0.7862) and for DWRS (R = 0.7254). This would mean that the higher the adequacy score, the higher the water savings value, when in theory the expected relationship would be a direct but negative correlation (higher water saving occurring when adequacy scores are lower). However, a negative direct correlation was observed when all the treatments were analyzed by season treatments F07 and S07 (R= -0.5639 and -0.5498, respectively). The highest overall water savings were seen during F07, which received the greatest amount of rainfall during the four treatment periods (McCready et al, 2009).

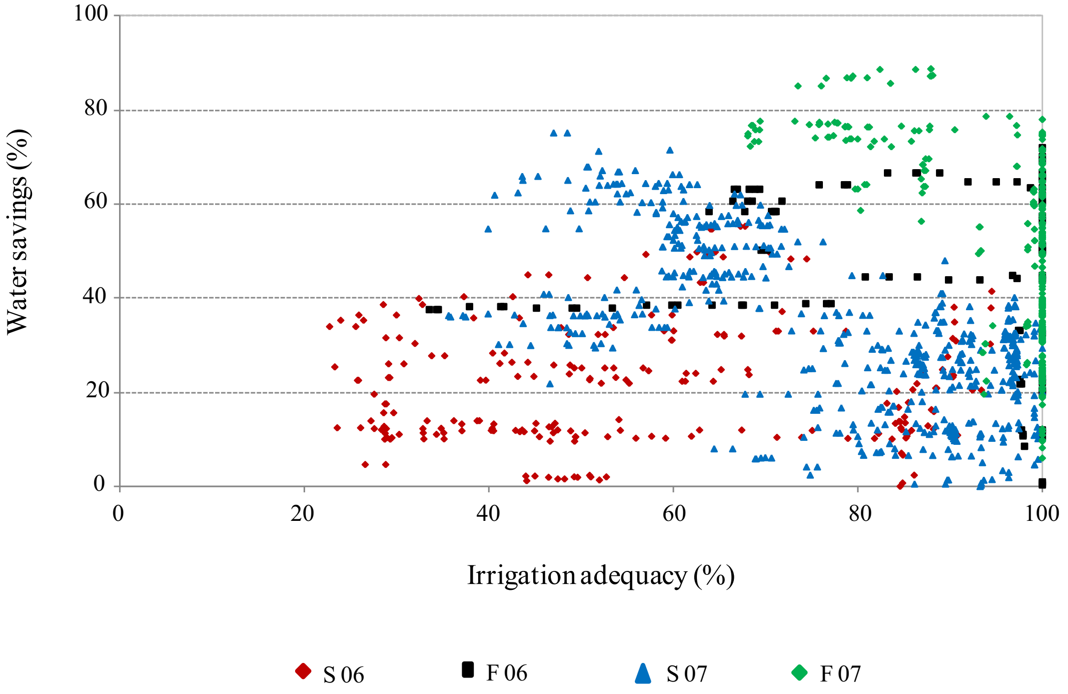

Figure 1: Water savings versus irrigation adequacy by seasons. S06 = spring 2006, F06 = fall 2006, S07 = spring 2007, and F07 = fall 2007.

Table 2: Correlation coefficients from multiple correlation analysis considering all treatments and by controller treatments.

Treatments		Gross irrigation	Water savings	Irrigation adequacy	Scheduling efficiency	Turf quality	30-day rainfall
ALL	G. irrigation[1]	1					
	W. savings	-0.7549	1				
	I. adequacy	-0.02869	0.0979	1			
	S. efficiency	-0.0883	0.0043	-0.3171	1		
	T.quality	-0.0375	0.1954	0.3906	0.1720	1	
	30-d rainfall	-0.2179	0.2896	0.3164	-0.4247	-0.0502	1
AC7	G. irrigation	1					
	W. savings	-0.9271	1				
	I. adequacy	-0.7337	0.7862	1			
	S. efficiency	0.3041	-0.2664	-0.4642	1		
	T.quality	-0.4510	0.6384	0.2519	0.1287	1	
	30-d rainfall	-0.3247	0.3388	0.6607	-0.8529	-0.0811	1
AC10	G. irrigation	1					
	W. savings	-0.8685	1				
	I. adequacy	-0.4295	0.4885	1			
	S. efficiency	-0.3881	-0.0559	-0.1594	1		
	T.quality	-0.3463	0.3997	0.6023	0.0176	1	
	30-d rainfall	-0.1894	0.2711	0.3399	-0.7683	-0.7683	1
TORO	G. irrigation	1					
	W. savings	-0.9612	1				
	I. adequacy	-0.0734	0.1412	1			
	S. efficiency	-0.5067	0.4703	-0.4178	1		
	T.quality	-0.3692	0.3250	0.1157	-0.2649	1	
	30-d rainfall	-0.1872	0.2219	0.2735	-0.2903	0.0899	1
RS1-6mm	G. irrigation	1					
	W. savings	-0.8358	1				
	I. adequacy	-0.3107	0.4368	1			
	S. efficiency	0.2146	-0.2606	-0.4443	1		
	T.quality	0.1409	0.0634	0.5807	0.1837	1	
	30-d rainfall	-0.4011	0.5542	0.3793	-0.2594	-0.0441	1
RS2-6mm	G. irrigation	1					
	W. savings	-0.6008	1				
	I. adequacy	-0.2047	0.2724	1			
	S. efficiency	0.4720	-0.4566	-0.4932	1		
	T.quality	0.2542	0.2737	0.2334	0.1073	1	
	30-d rainfall	-0.1813	0.4435	0.3357	-0.4682	-0.0779	1
RS7-3mm	G. irrigation	1					
	W. savings	-0.7446	1				
	I. adequacy	-0.2697	0.5265	1			
	S. efficiency	0.6989	-0.6225	-0.5782	1		
	T.quality	0.0647	0.3077	0.8709	-0.3478	1	
	30-d rainfall	-0.3459	0.4374	0.3821	-0.2066	0.1537	1
DWRS	G. irrigation	1					
	W. savings	-0.6566	1				
	I. adequacy	-0.7602	0.7254	1			
	S. efficiency	0.1564	-0.1499	-0.0896	1		
	T.quality	-0.0442	0.3835	0.2240	0.4935	1	
	30-d rainfall	-0.3388	0.5442	0.4665	-0.3348	-0.1609	1

[1] G. irrigation= gross irrigation, w.savings = water savings, i.adequacy = irrigation adequacy, s. efficiency = scheduling efficiency, t. quality = turfquality, 30-d rainfall = 30-day rainfall.

3.2 Scheduling efficiency versus water savings

The expected positive and direct correlation between water savings and scheduling efficiency was not observed when all treatments were considered together (R value was 0.0043; Figure 2, Table 2). When evaluating each controller treatment, correlation values were negative, especially with the three rain sensor treatments, except with the TORO controller, that showed an R value of 0.4703. Rain sensors may not take into account rainfall perfectly, which led to lower scheduling efficiency. As with the irrigation adequacy scores, there were high score values associated with both, high and low water savings (Figure 2, Table 2). But when all controller treatments were evaluated by season, F06, S07 and F07 showed positive correlations, although the R values were low (R=0.3292, 0.3163 and 0.3342, respectively).

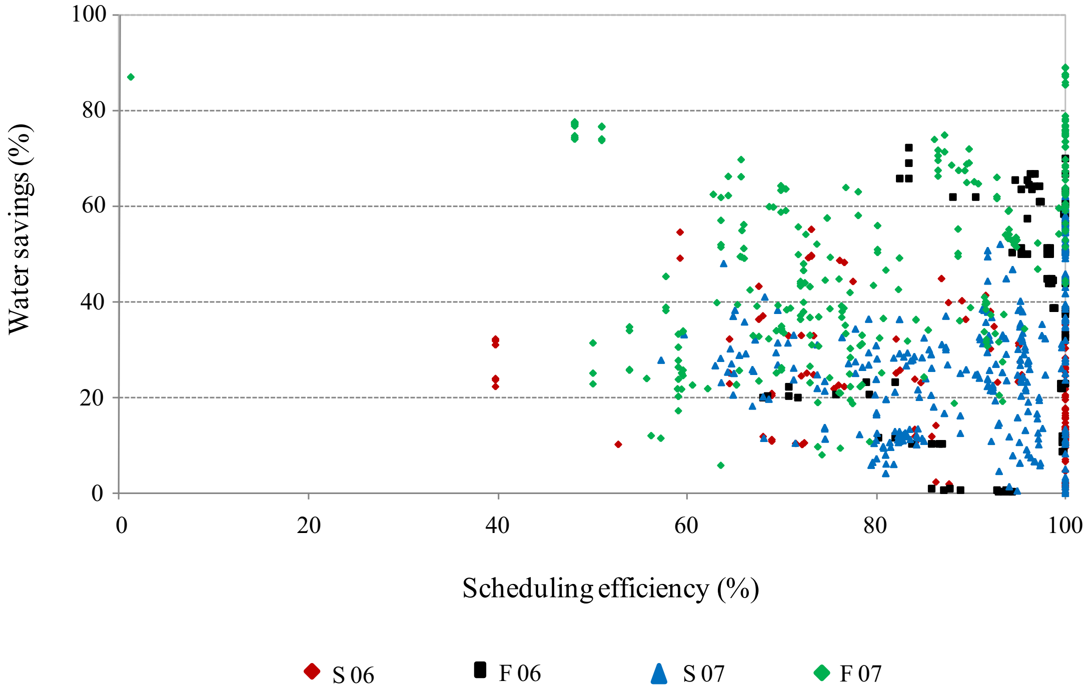

Figure 2: Water savings versus scheduling efficiency by seasons. S06 = spring 2006, F06 = fall 2006, S07 = spring 2007, and F07 = fall 2007.

3.3 Turf quality versus SWAT scores

Turf quality values from 4.0 to 8.0 were related to a range of irrigation adequacy scores that ranged from 20 to 100%, showing an R=0.3905 (Figure 3a, Table 2). Considering all controller treatments, the correlation was positive, with an R = 0.3905. In some cases, irrigation adequacy was very low (30%) and turf quality was still acceptable (7.0). On the other hand, there were cases were irrigation adequacy was higher than 80% and turf quality included a 4.0 rating. The RS7-3mm controller treatment showed the highest correlation with irrigation adequacy (R=0.8709), showing adequacy scores from 80 to 100% correlated with turf quality of 6.0 and 7.0, respectively. This treatment was followed by AC10 (R=0.6023), which showed lower adequacy scores from 40% to 100% correlated with turf quality from 5.0 to 7.0. The rest of controller treatments showed positive low correlation values (R < 0.5; Table 2). Considering all treatments by season, F07 showed the highest correlation with irrigation adequacy (R=0.6194). This treatment period showed acceptable turf quality rating (5.0) even in then non-irrigated plots, because of frequent rainfall.

Scheduling efficiency scores for all treatments showed a positive but low correlation with turf quality ratings (R=0.1720; Figure 3b; Table 2). Scheduling efficiency would not be expected to increase turf quality but it is important to note that did not decrease turf quality. Scheduling efficiency ranged from 40% to 100% for turf quality ratings ranging from 4.0 to 8.0. Analyzing every controller showed no correlation at all. Analyzing by season treatment, only S06 and F06 showed positive correlations with R=0.5137 and R=0.5735, respectively (Table 3). These two seasons were relatively dry and all the technologies tested managed to reduce water application (McCready et al., 2009), meaning a high efficiency of irrigation while turf quality was still acceptable.

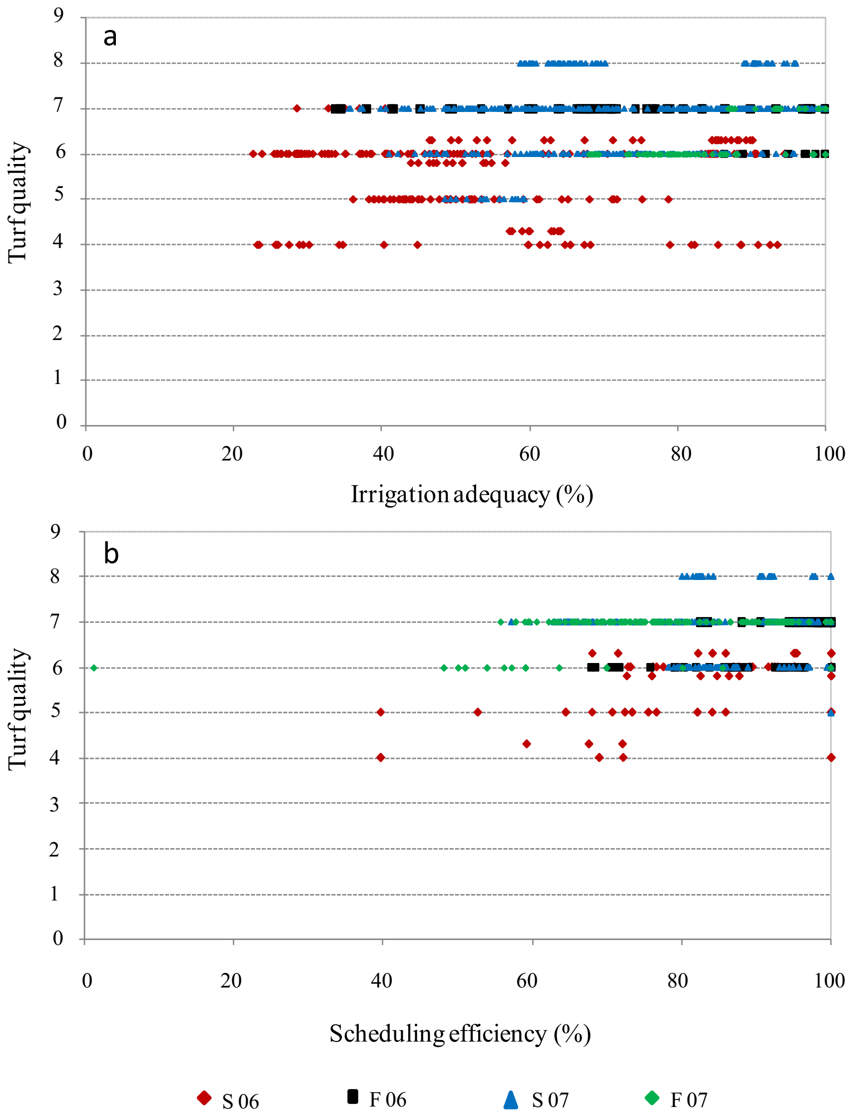

Figure 3: Turf quality versus irrigation adequacy (a) and scheduling efficiency (b) across seasons. S06 = spring 2006, F06 = fall 2006, S07 = spring 2007, and F07 = fall 2007.

3.4 Rainfall amount and SWAT scores

There was a positive correlation between 30-day period rainfall and irrigation adequacy when all the controller treatments were analyzed (R=0.3164; Figure 4a; Table 2), which means the higher the cumulative rainfall, the lower the irrigation input, and the higher the irrigation adequacy. The only controller treatment showing the highest correlation was treatment AC7, with an R= 0.6607. The rest of the controller treatments showed correlation values lower than 0.5 (Table 2). When the correlation analysis was done by season treatment, S06 was the only treatment showing a positive correlation with an R=0.5328, while the remaining treatments did not show any correlations at all (Table 3). Relationship between the 30-day period rainfall and scheduling efficiency show an inverse correlation when all treatments were considered (R= -0.4247, Figure 4b). This would mean that for a higher cumulative rainfall amount, a lower irrigation application corresponded. Scheduling efficiency tended to decreased because of timing of rainfall during the soil water balance. In the soil water balance, the rainfall occurs before irrigation, causing drainage to occur from irrigation. The analysis by seasonal treatment showed no correlation between cumulative rainfall and scheduling efficiency.

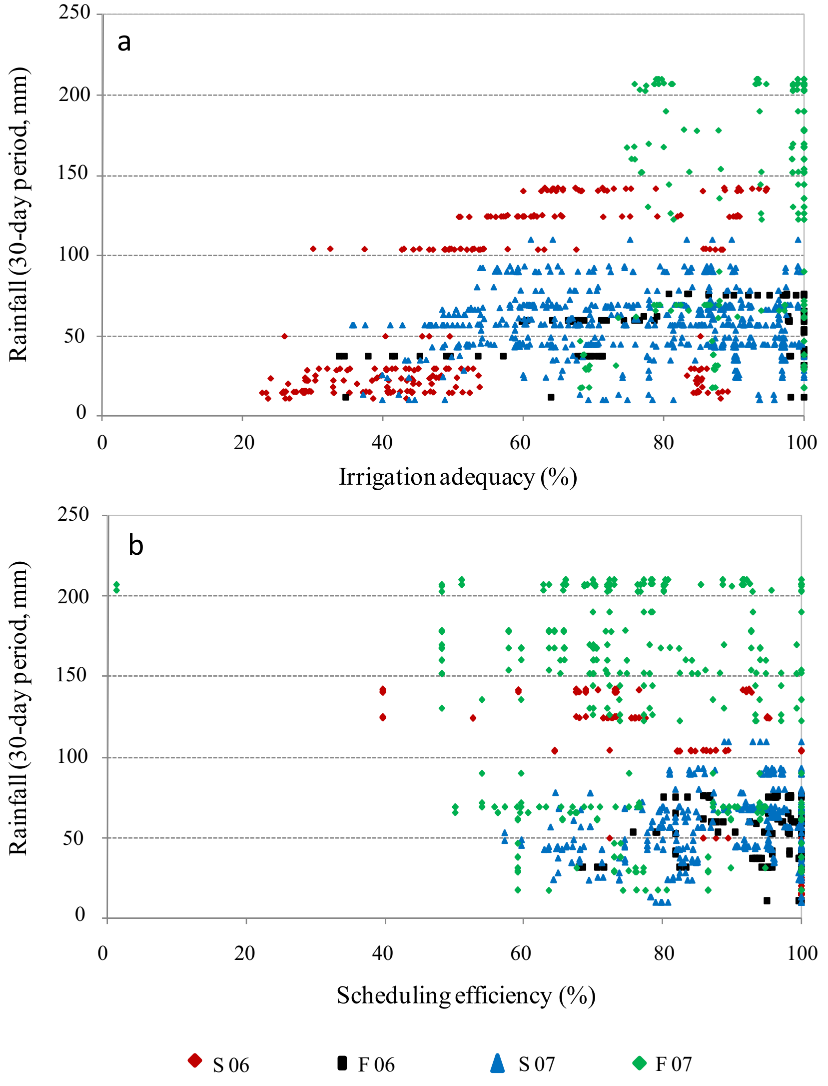

Figure 4: Thirty day cumulative rainfall versus irrigation adequacy (a) and scheduling efficiency (b) across seasons. S06 = spring 2006, F06 = fall 2006, S07 = spring 2007, and F07 = fall 2007.

Table 3: Correlation coefficients from multiple correlation analysis (analysis by season).

Treatments		Gross irrigation	Water savings	Irrigation adequacy	Scheduling efficiency	Turf quality	30-day rainfall
S06	G. irrigation	1					
	W. savings	-0.8571	1				
	I. adequacy	0.0869	0.1364	1			
	S. efficiency	0.1639	-0.4446	-0.3016	1		
	T.quality	0.0682	-0.1919	0.0071	0.5137	1	
	30-d rainfall	-0.2379	0.5841	0.5328	-0.8009	-0.2905	1
F06	G. irrigation	1					
	W. savings	-0.7977	1				
	I. adequacy	-0.0441	-0.2214	1			
	S. efficiency	-0.1422	0.3292	-0.3492	1		
	T.quality	-0.3917	0.5346	-0.3781	0.5735	1	
	30-d rainfall	-0.1882	0.0093	0.1507	0.0801	-0.2543	1
S07	G. irrigation	1					
	W. savings	-0.7945	1				
	I. adequacy	0.5356	-0.5498	1			
	S. efficiency	-0.5316	0.3163	-0.4717	1		
	T.quality	-0.2064	0.1377	0.2069	0.02744	1	
	30-d rainfall	-0.0844	-0.0348	-0.0050	0.1706	-0.3401	1
F07	G. irrigation	1					
	W. savings	-0.8701	1				
	I. adequacy	0.6253	-0.5639	1			
	S. efficiency	-0.3292	0.3342	-0.0002	1		
	T.quality	0.3349	-0.2455	0.6194	0.3126	1	
	30-d rainfall	0.1911	0.0105	0.0681	-0.2132	0.0665	1

[1] G. irrigation= gross irrigation, w.savings = water savings, i.adequacy = irrigation adequacy, s. efficiency = scheduling efficiency, t. quality = turfquality, 30-d rainfall = 30-day rainfall.

3.5 Testing SWAT scores in time

In terms of SWAT testing, controller will (almost) get good scores if testing occurs for a long enough time period. We analyzed the temporal average considering one season (S06), two seasons (S06+F06) and so on, of irrigation adequacy and scheduling efficiency. The results showed that the average irrigation adequacy increased when more evaluations were considered (Figure 5a). This trend was observed for all the controller treatments. However, this trend was not observed for scheduling efficiency (Figure 5b). Scores were high or low for at least some 30 day period. Since the variability is high we would propose that multiple 30 day periods need to be used for evaluating controllers

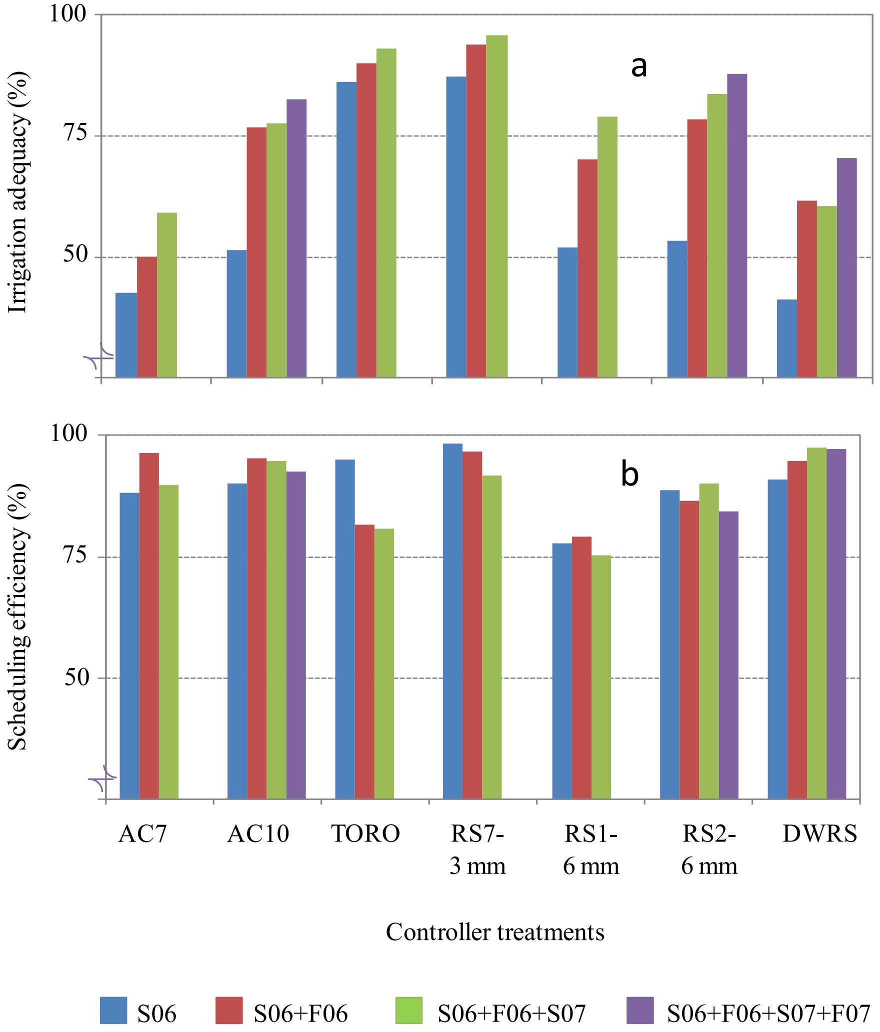

Figure 5: Effect of long-term evaluation irrigation controllers on irrigation adequacy and scheduling efficiency. S06 = spring 2006, F06 = fall 2006, S07 = spring 2007, and F07 = fall 2007.

4. Conclusions

There is a not a clear trend for water conservation with either higher scheduling efficiency or higher irrigation adequacy scores evaluated under field conditions. Also, turf quality remained acceptable (5.0) even when adequacy scores were as low as 30%. In SO6 the general trend was that as efficiency increased, water savings decreased, which was the opposite of the other testing periods. There were some cases where irrigation efficiency reached low values (around 50%) but high water savings (75%) during F07 under treatment AC7. These results indicate that the values used in the SWAT analysis soil water balance need to be verified against field data, particularly for irrigation adequacy. There was a positive correlation between 30-day period rainfall and irrigation adequacy but negative with scheduling efficiency. Thus, the overall indication is that rainfall during the testing period can contribute to increased adequacy scores and decreased scheduling efficiency scores, indicating that the controllers tested here did not perfectly account for rainfall or the soil balance does not perfectly capture the actual conditions. In all cases, less gross irrigation led to increased water savings.

As described by Mayer et al. (2009), the SWAT testing protocol was not designed as a way to assess water savings, but rather is a method to try and ensure controllers apply the right amount of water based on current ET formulation. If water efficiency or irrigation adequacy are the primary goal of the testing regime, then a conservation-oriented testing criteria perhaps derived from the current SWAT protocol should be considered. Historical water use compared to estimated irrigation need of a site with a new smart controller may be one of the most important things to determination of water savings. Future testing should evaluate the SWAT protocol analysis against field installations and to develop optimized programming for various technologies to promote water conservation.

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Maximizing Effective Agronomics in Landscapes with Soil Moisture Sensors

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Abstract. *The key information required to make agronomically sound irrigation decisions is reviewed, including the relative relationships of soil type, soil water holding characteristics, and plant water requirements. Optimal water management and the agronomic relationship between plants and soils is discussed. The relative benefits and challenges of weather based and soil moisture based irrigation decision making are reviewed. Specific capabilities of soil moisture based irrigation controls are discussed with implications for long term performance, control, and effectiveness. Relative performance of various soil moisture measurement techniques are reviewed, and an overall summary of agronomic benefits of various smart watering approaches is provided.*

Keywords. Smart controller, smart irrigation, ET, evapo-transpiration, soil moisture sensor, SMS, agronomy, soil science, water management, irrigation scheduling, sprinkler, sprinkler controller, irrigation controller, rain sensor

Introduction

The purpose of this white paper is to provide a short overview of landscape irrigation watering issues associated with irrigation controls, and review the various alternatives for improving watering performance in landscape applications.

This white paper references a breadth of original and derivative research in North America and worldwide. While this paper merely scratches the surface of historic and recent research conducted in the area of landscape and agricultural irrigation efficiency, it is the intention of the author to illustrate the potential value of new technologies available to the irrigation industry to affect widespread reduction in outdoor water use while maintaining or improving the quality of residential and commercial landscapes.

The intent of this paper is to focus on the agronomic issues associated with the plant-soil-water system with respect to the various new technologies, including soil moisture sensors (SMS). The availability of inexpensive, highly accurate, and reliable soil moisture sensors is possibly the most agronomically important landscape irrigation development of the last 20 years.

Overview of Landscape Irrigation Water Waste Issues

The use of irrigation water for urban landscapes has grown materially in the United States over the last two decades in conjunction with the increase in automated irrigation systems.

It is important to note that automated irrigation systems provide meaningful benefits to the U.S. and International consumers. These benefits include, but are not limited to:

- Convenience
- Consistent health and beauty of landscapes
- Ability to support landscapes in arid climates

However, it is also clear that one unanticipated result of this proliferation of automated irrigation systems is the consistent and epidemic overwatering of most North American landscapes.

The problem: Overwatering, Not Water Use

The purpose of this paper is to focus on overwatering behaviors and their agronomic implications. However, the author feels it necessary to state very clearly that the problem is over-watering, not water use. Appropriate water use to support landscapes is a significant factor in the North American quality of life, and a social expectation of most citizens of the United States.

While appropriate changes in planting materials, application technologies, local regulations and local restrictions are appropriate limits on water use, the focus of this paper is on overwatering. This is both a technical and behavioral issue for commercial and residential landscape management in the United States.

Scope of the Overwatering Problem in Landscapes

The most commonly accepted urban water use statistic come from the American Water Works Association, which estimates that water use for U.S. domestic landscapes averages 58%.

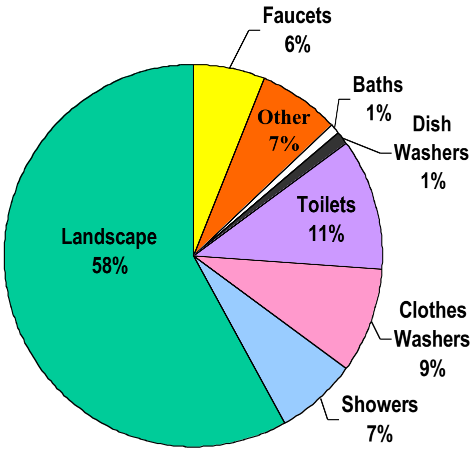

Figure 1. Domestic Water Use in the United States.
Source: AWWA End Uses of Water, 2001.

Of this water applied to domestic landscapes, the Environmental Protection Agency estimates that as much as 50% is wasted. This results in roughly 3.5 billion gallons of water waste per day in the United States alone. While concrete measures of the actual cost of wasted water in the United States, most sources size the total U.S Dollar value of the waste as between $2.0B and $2.4B, annually.

Other Effects of Overwatering

While there are many social and environmental effect from overwatering irrigated landscapes, most sources classify the affects as follows:

- Energy consumption for pumping and distribution
- Capital costs for treatment and management
- Runoff issues, including impacts to wetlands and costal coral reef systems
- Plant health

The conclusion is obvious and difficult to ignore: overwatering is not only a tangible multi-billion dollar problem in the United States, but has significant social and environmental impacts as well.

Sources of Overwatering in Irrigated Landscapes

There are clearly a variety of sources of overwatering in irrigated landscapes. For the purposes of treatment, the root causes for landscape overwatering are most often classified as follows:

Table 1. Most Common Root Causes of Overwatering in the United States

System Design	Examples: • Poor distribution uniformity o Improper application technology chosen o Improper head placement o Mixing of application technologies • Mixing of plant materials with different water needs • Improper design for topography and slopes
Installation Quality	Examples: • Improper placement of heads, plant materials, and or landscape features • Failure to comply with manufacturer's instructions • Improper or incomplete inspections
Maintenance	Examples: • Broken or unadjusted sprinkler heads • Blocked heads due to grow in or landscape changes • Leaks
Programming/Scheduling	Examples: • Excessive, unmeasured watering times • No seasonal adjustments • Application rates in excess of soil infiltration rates • No adjustments based on actual soil moisture conditions • Failure to water deeply and infrequently to promote deep root growth and drought tolerance

It is increasingly clear that all of these areas must be treated, and programs from the Irrigation Association and the U.S. Environmental Protection Agency have begun to address all the root causes listed above.

The remainder of this paper will focus on the last item: automated irrigation system programming and scheduling. While technical advances in other areas have facilitated potential improvements, the low cost and high efficacy of scheduling technologies makes this an area of specific interest to affect wide scale in the United States and world-wide.

Restrictions: A Temporary Solution With Costs

Watering restrictions are a common and increasing technique for water purveyors to control landscape irrigation use at the state and local level. Broad use of watering restrictions, in most areas with associated fine structures, has grown dramatically U.S. wide over the last 10 years.

However, watering restriction programs are rarely founded on sound, if any, agronomics. Most watering restriction programs are effectively a position of last recourse for the municipalities involved, and have the generalized effect of stressing or even permanently damaging

While the scope of landscape damage due to watering restrictions has not been well studied, the author suspects that the total cost in landscape damage may exceed the total value of water saved. Further study in this area is suggested.

The author further posits that, given a choice between spending a modest amount on appropriate technologies to treat overwatering problems or suffering damage and degradation to landscape quality, most Americans would opt for the former.

Potential Solutions to Overwatering in Irrigated Landscapes

As has been covered elsewhere at length, there are many potential solutions to overwatering issues in irrigated landscapes. As with the root causes listed in Table 1 above, most classify the potential solutions as follows:

Table 2. Potential Solutions to Overwatering in Irrigated Landscapes

System Design	Examples: • Matched precipitation rate application technologies • Increased use of micro and subsurface drip technologies • Increased use of pressure regulation • Proper pipe sizing and hydrological design • Use of native or area appropriate plant materials • Restrictions on total turf areas as a percentage of landscapes • Restrictions on inappropriate application designs (e.g. spray heads on steep slopes)
Installation Quality	Examples: • Certifications or licensing for irrigation installers • Increased manufacturer training and certification programs • Increased inspection programs
Maintenance	Examples: • Maintaining proper maintenance schedules • Keeping heads and other equipment properly adjusted • Replacing worn or broken equipment • Detecting and fixing leaks
Programming/Scheduling	Examples: • Deployment of smart control technology to better determine when and how much water to apply • Match application rate to infiltration rate • Minimize evaporation loss • Minimize leaching loss • Minimize runoff • Minimize disease and parasites

	• Avoid landscape use damage due to over-wet or over-dry conditions for multi-use landscapes

Clearly, all of these areas should be considered and evaluated when attempting to address overwatering issues.

The key question is: which technologies and approaches will be the most effective in changing watering behavior in the United States and world-wide?

Programming/Scheduling Factors for Landscape Irrigation

The purpose of this section is to review the scheduling factors typically used to control landscape irrigation, and the key questions that must be answered to optimally apply landscape water.

Studies in wet climates such as Florida and the South Eastern U.S. indicate that scheduling solutions alone, independent of other treatments, can result in a 70% reduction in outdoor water use.

Studies in dry climates such as Utah indicate that residential systems in these regions over-water by at least 50%, irrespective of rainfall.

The potential for water use reduction through the reduction or elimination of overwatering due to irrigation scheduling should not be underestimated. Based on research to date, the author estimates that water savings from simply improving irrigation controls to be as follows:

Table 3. Potential Water Savings From Landscape Irrigation Scheduling Changes Alone

Wet Climate	Up to 70% of landscape water use can be reduced by making smart control (scheduling) changes alone, independent of additional improvements in application uniformity and system design.
Dry Climate	Up to 40% of landscape water use can be reduced by making smart control (scheduling) changes alone, independent of additional improvements in application uniformity and system design.

While these claims may seem bold, the author is excited to see a growing body of supportive literature and is excited to see the results of these ongoing investigations.

Scheduling Questions:

When scheduling irrigation, the key questions that should be considered include the following:

- When to irrigate?
    - Is nighttime application recommended to reduce evaporation
    - What restrictions apply?
    - What landscape use is expected?
- How much water to apply?
- How quickly can water infiltrate into the soil?
    - How quickly does water run off sloped areas?
- How quickly does the application technology apply water?
- How much variability (distribution uniformity) is there in application rates due to system design or condition?
- What is the plant water requirement?
- How much water can the soil hold?

- What is the health of the plant material?
- What nutrition levels are currently available in the soil?

Various “smart control” technologies attempt to answer some or all of these questions. This paper will contrast the most prevalent technologies and solutions as to their ability to answer these key scheduling questions.

However, it is clear that there are significant differences between the capabilities of the different approaches.

Soil Water Holding Characteristics

By way of analogy, the soil is the plant’s “drinking water storage tank”. Like any storage tank, soil water holding comes in many shapes and sizes. Some tanks can be filled faster than others. The time between fillings (to keep the tank from becoming completely empty) depends on how fast the water is being used and the total holding capacity of the tank.

Likewise, soil systems have natural capability to store and hold water. Also, most plants have evolved to tolerate significant variation in soil moisture conditions as driven by common weather patterns in their native region(s).

In order to optimally schedule irrigation, precise knowledge of the holding capacity of the soil is highly desired. To return to the tank analogy – if you were designing a tank-filling system, would you want to know when the tank was empty and/or full?

Modern technologies such as soil moisture sensors are capable of providing exactly this information.

Soil Moisture Terminology

Soil moisture content is typically described with the following terms:

Table 4. Soil Moisture Content Terms and Definitions

Saturation	When a soil is saturated, the soil pores are completely filled with water and nearly all of the air in the soil has been displaced by water. Gravity will exert force on the water contained in saturated soils, moving it deeper into the ground (if possible). This is known as “gravitational water”.
Field Capacity	The level of soil moisture left in the soil after drainage of the gravitational water. Irrigation to levels above field capacity will result in runoff or drainage as gravitational water.
Managed/Maximum Allowed Depletion (MAD)	The desired maximum soil moisture deficit at the time of irrigation. Soil moisture levels below MAD are not desired, and may result in stress or permanent wilting of plant materials. Most systems use a safety factor to set MAD above the permanent wilt point.
Oven Dry	When soil is dried in an oven, nearly all water is removed. This moisture content is used to provide a reference for measuring saturation, field capacity, and MAD.

A key soil holding capacity concept is that soil saturation is greater than field capacity. Imagine a sponge dipped in a bucket. When removing the sponge from the bucket, water will drip from the sponge for a period of time. When this dripping has stopped, the sponge will be at its field capacity. Squeezing the sponge will result in additional water running out.

Likewise in soil systems, within the area of interest for the roots of the plants in the landscape, application of water above field capacity is excess irrigation, and will gravitationally move through the root level into deeper soil.

A second key concept is that the amount of water required to change the soil moisture level from MAD to field capacity is constant. If precise irrigation can be timed to occur when and every time the MAD has been reached, the exact same amount of water application will result in filling the soil to field capacity and no further. This is regardless of season, temperature, or plant need.

Soil Types and Water Holding Characteristics

The USDA defines soil textures via relative composition of particle sizes. Particle sizes are roughly grouped in the following categories:

- Gravel
- Sand
- Silt
- Clay

Figure 2 shows the relative sizes of these particles.

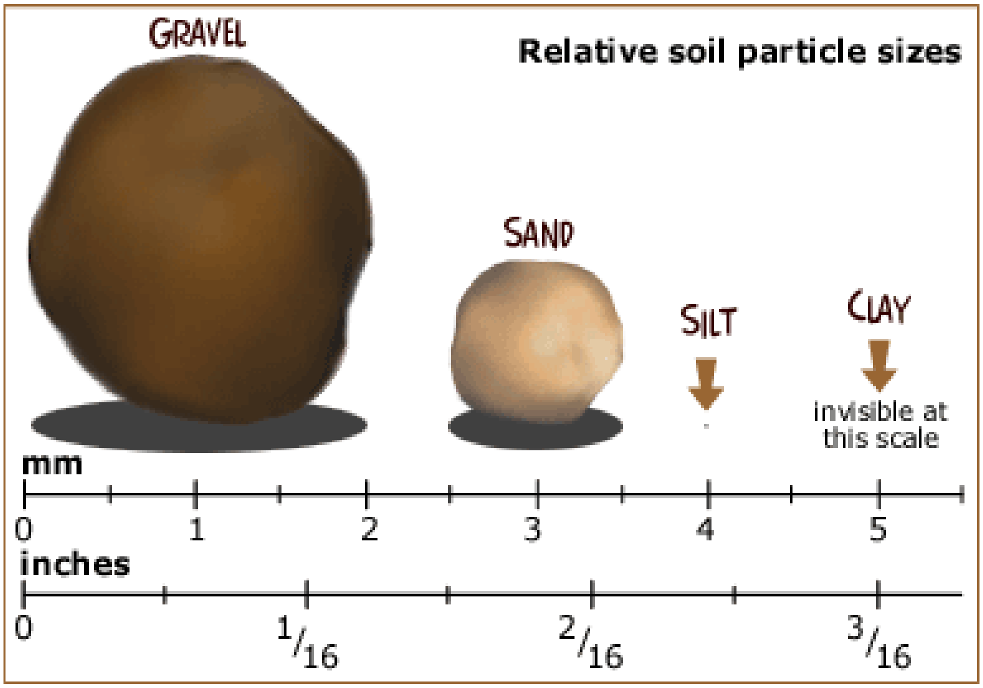

Figure 2. Relative sizes of soil particles
Chart courtesy of IFAS, University of Florida

Specific soil typing is generally accomplished using the USDA Soil Textural Triangle:

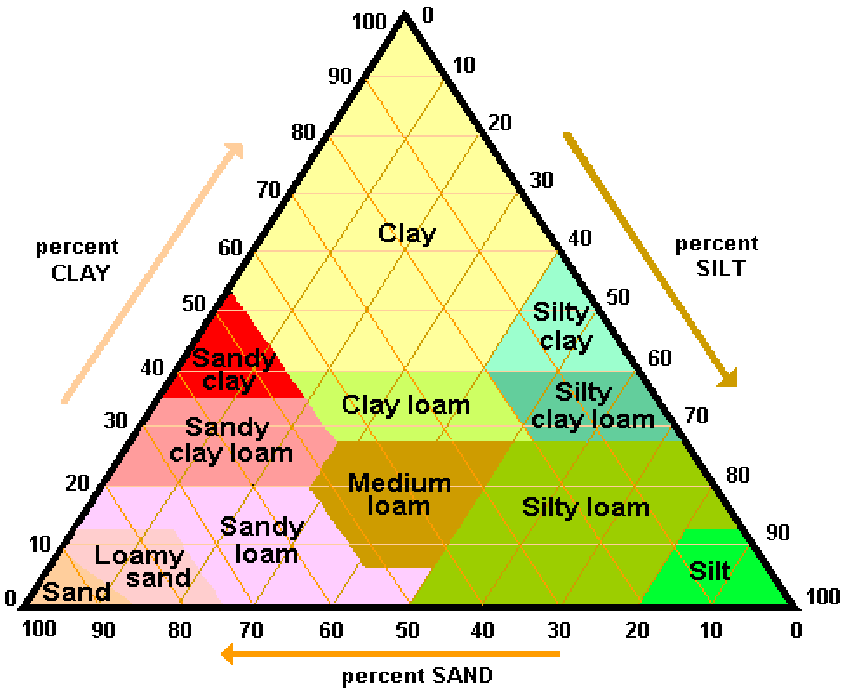

Figure 3. USDA Soil Textural Triangle
Chart courtesy of the USDA

The most significant irrigation issue with respect to soil type is that most irrigators have no idea what soil type they have. This makes optimum irrigation scheduling difficult if not impossible.

Careful analysis of soil moisture data provided by modern soil moisture sensors can determine field capacity for any soil type. This capability enables irrigation control functions such as automated determination of field capacity and MAD for specific hydrozones in an irrigated landscape.

Key Point: Automated irrigation control systems with soil moisture sensors can be configured not only to apply more or less water per application, but also to appropriately vary the time between irrigations. Irrigation is required more frequently in sandy soils than in heavy or clay soils.

Soil Condition Also Affects Holding Capacity

In addition to the particulate sizes in the soil, conditions of the soil can also affect water holding capacity. While an exhaustive review of these conditions is beyond the scope of this white paper, two specific common conditions affecting irrigated landscapes are mentioned here.

First, soil density can have a very significant affect on water holding capacity of soils. This is particularly an issue for new construction projects, where the soil has been significantly perturbed as a part of the construction and landscaping process.

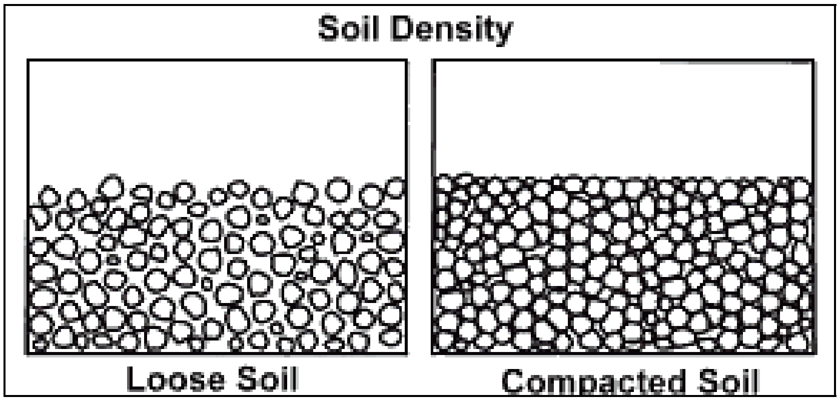

Figure 4. Soil Density
Image courtesy of the University of Minnesota Agricultural Extension

Water holding affects of uncompacted or compacting soils are difficult to estimate. Technologies such as soil moisture sensors, when installed in similarly disturbed soil conditions, provide the best insight into changing holding characteristics.

A second common soil condition affecting holding capacity in irrigated landscapes is soil layering.

Figure 5. Soil Layering Example
Image courtesy of the USDA

Soil layering is most specifically an issue when amended soils (i.e., top soil) has been applied over a layer of heavier compacted soil. This creates a barrier to gravitic water movement, and may also create a barrier to deeper root growth.

In these cases, the mechanical motion of water, and the resultant affects on field capacity and MAD can be difficult to estimate.

Key point: Soil moisture sensors can be an effective tool for monitoring actual moisture conditions even in the event of complex compaction or soil layering scenarios.

Optimum Irrigation Scheduling vs. Soil Moisture Content

The target of optimum irrigation is to keep the soil moisture (plant available water) between the soil's Field Capacity and a Maximum Allowed Depletion point. With the exception of specialty irrigation applications such as syringe cycling or post fertilization watering, all applied irrigation, regardless of the technique or technology used attempts to accomplish this.

However, as outlined in the section above, both Field Capacity and MAD vary by soil composition. A simplified graph of the relationship soil moisture content and soil composition is show in Figure 6.

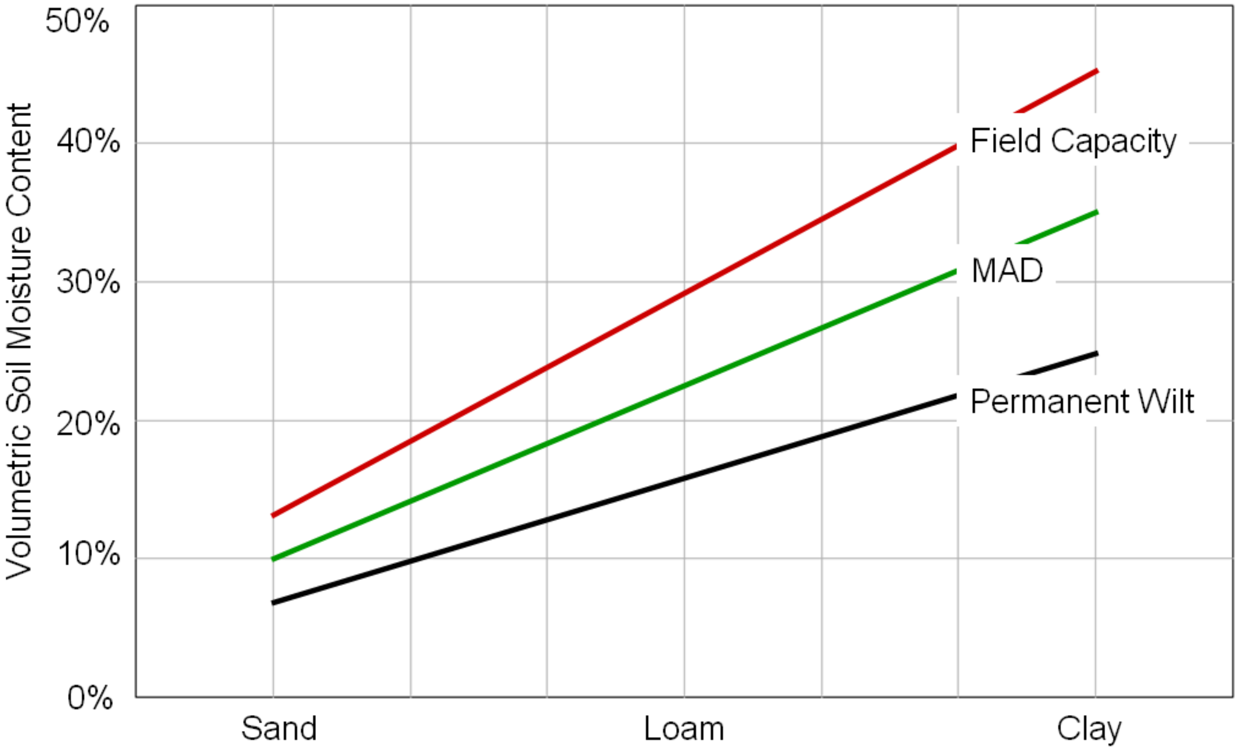

Chart for example purposes only

Figure 6. Simplified Example of Soil Holding Characteristics

As stated above, the objective of all artificial irrigation is to dry the soil conditions out to the MAD, then apply the minimum amount of water required to return to Field Capacity. This is true regardless of soil type or plant need.

Key point: Precise measurement of soil moisture simplifies and optimizes the potential for optimal watering behavior, and protects against landscape damage due to inadvertent mis-estimation of field capacity or permanent wilt point.

Plant Water Needs

Another key characteristic of optimal irrigation is understanding plant need. Plant water needs have been studied extensively in Agriculture over the last 70 years. Early work in the field resulted in the articulation and characterization of the plant-soil evapo-transpiration system. Evapo-transpiration (“ET”) estimates the soil moisture depletion based on measurable weather or climate data in order to determine how much water to apply. Several different calculations exist, using a superset of subset of a set of key weather variables, including solar radiation, high and low air temperature, wind exposure, and humidity.

This watering model (modification of applied water based on plant water need) is often referred to as “deficit irrigation”.

Key point: Modern soil moisture based control solutions can precisely measure the affects of these same weather variables as they apply to the actual level of moisture in the soil – the very metric that the calculations were invented to estimate.

The basic water need of plants is most strongly affected by the variables used in the ET calculations, but are also affected by many other variables to a lesser degree.

However, one important area of additional impact in landscape applications is from plant nutrition and health. Plant nutrition can, especially when under-fed, result in poor looking plants regardless of how much water is applied. This concept is most clearly explained using Leibig’s Barrel.

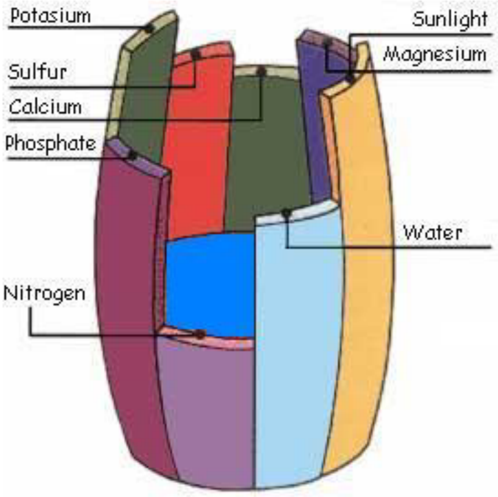

Figure 7. Liebig’s Barrel

Liebig's Law of the Minimum, often simply called Liebig's Law or the Law of the Minimum, is a principle developed in agricultural science by Carl Sprengel (1828) and later popularized by Justus von Liebig. It states that growth is controlled not by the total of resources available, but by the scarcest resource (limiting factor).

This concept was originally applied to plant or crop growth, where it was found that increasing the amount of plentiful nutrients did not increase plant growth. Only by increasing the amount of the limiting nutrient (the one most scarce in relation to "need") was the growth of a plant or crop improved.

Key point: Soil moisture based irrigation control systems automatically account for actual plant water use as limited by the most limited resource. If more fertilizer is applied, and as a result more water is used by the plants, then additional water can be automatically applied.

Key point: Soil moisture based irrigation control systems will not automatically apply additional un-needed water when plant health is compromised due to low nutrient availability, thereby making the problem worse.

Key point: “It is all ET” – (quoted from Brent Mecham, Irrigation Association.) While there often seems to be an argument between weather based and soil moisture based control solutions, the bare truth is that these are all methods for watering to ET. “ET” is the description of the system, not the watering technique.

Root Depth, Drought Tolerance and Plant Health

Most plants, and nearly all turfgrass varietals, respond to mild soil moisture stress with root growth. For this reason, the rule of thumb for watering established lawns, especially in more arid climates, is to water as deeply and infrequently as possible.

Deeper root systems result in healthier plants, more drought tolerance, more disease resistance and more nutrient uptake efficiency. Further, in many cases proper irrigation management can increase plant health and also reduce the use of pesticides. This technique has been used in Agriculture for over 30 years.

Key Point: Automated irrigation controllers with soil moisture sensors can safely water more infrequently, allowing MAD to always be reached without the risk of permanent wilt or plant damage. This naturally results in healthier, more drought tolerant, more disease resistant plants.

Evapo-Transpiration and Crop Coefficients

One of the variables in ET calculation is the crop coefficient (Kc). Crop coefficients are generally the result of agricultural study, and are designed to work with maximum growth for maximum harvest. This crop growth model assumes that water availability is not the limiting factor. Colloquial reference to this growth model in turf grass is often termed “bailing mode.”

Since it has been well determined that deficit irrigation improved plant water use efficiency (WUE), it also seems clear that optimal watering will actually require less applied water than estimated by ET using standard crop coefficients.

Further study implies that many landscape cultivars exhibit peak water use curves that do not line up in time with established ETo.

Field testing of modern weather based and soil moisture based irrigation control solutions implies that soil moisture based solutions are not only more likely to easily produce excellent water use reduction results, but in fact may irrigate more optimally than ET calculations would predict.

Key point: Automated irrigation control systems with soil moisture sensors often demonstrate water savings in excess of those predicted by ETo while maintaining excellent plant health and visual quality.

Rainfall and Effective Rainfall

When determining irrigation watering needs, natural rainfall should be accounted for. However, in order to determine the Effective Rainfall, i.e., the amount of natural rainfall that infiltrates the soil and is available to plants, the infiltration rate of the soil must be considered.

Table 5. Estimated Infiltration Rates for Common Soil Types

Course Sand	0.75” to 1.00” per hour
Fine Sand	0.50” to 0.75” per hour
Find Sandy Loam	0.35” to 0.50” per hour

Silt Loam	0.15” to 0.40” per hour
Clay Loam	0.10” to 0.20” per hour

Rainfall at a rate in excess of the soil’s infiltration rate will most often run off if there is any appreciable slope to the landscape.

Key point: One benefit of soil moisture based irrigation control systems is that the water that penetrates to the root zone, i.e., the Effective Rainfall, is automatically detected. When effective rainfall is not sufficient for plant need, the appropriate amount of additional irrigation can be automatically scheduled.

Options for “Smart” Programming/Scheduling

Technology has advanced significantly over the last 10 years in landscape irrigation. In addition to broad application of best practices from Agriculture, new solutions for the landscape irrigation industry have also been developed.

For programming & scheduling optimization, the most important of these developments are the so-called “smart controllers”. The Irrigation Association defines smart controllers as:

> “Smart” sprinkler controllers reduce outdoor water use by monitoring and using information about site conditions (such as soil moisture, rain, wind, slope, soil, plant type, and more), and applying the right amount of water based on those factors—not too much and not too little—to maintain healthy growing conditions. [Courtesy, the Irrigation Association.]

Smart controllers hold great promise to effectively reduce water use and increase plant health. Options for modern irrigation managers available today to do “smart” watering include:

Hands-on water management

- Hose end watering/visual examination of plant materials
- Manual operation of automated systems
- Timer programming using historical “ET” and seasonal adjustments

Climatology/Weather Based Controllers (“ET”)

- On-site weather stations
  - Tipping rain buckets
  - Evaporation devices
- Offsite weather data access

Soil Moisture Based Controllers (“SMS”)

- Newer techniques
  - Time Domain Transmission (“TDT”)
  - Frequency Domain Reflectometry (“FDR”)
- Older techniques
  - Electrical conductivity probes
  - Electrical conductivity in granular matrix
  - Tensiometers

Weather Based Irrigation Control “ET”

Use of automated weather based or “ET” irrigation controls has been common on commercial properties for the last 15 to 20 years. Weather based or “ET” controllers in general are devices which calculate or adjust irrigation schedules based on one or more of the following parameter sets: weather conditions (temperature, rainfall, humidity, wind and solar radiation), plant types (low versus high water use and root depth), and site conditions (latitude, soils, ground slope and shade).

Weather based controllers can get the necessary data to calculate ET from one or more of several sources:

- Historic Evapotranspiration data for the appropriate region or location
- On-site collected weather data
- Remotely collected and/or interpolated weather data

The relative benefits and challenges of these techniques are illustrated in the table below:

Table 6. Benefits and Challenges of Different Weather Based Control Approaches

Approach	Benefits	Challenges
Historical data	• No maintenance • Generally inexpensive • Relatively low tech • Good performance in non-peak water use periods	• Accuracy depends on variables • Does not respond to rapid changes or variability in weather • System uses generalized off site data
Remotely collected weather data	• No local maintenance • Reduction in both peak and non-peak water use • Data is generally from high-quality collection equipment • Can adjust for rapid change or variable weather	• Typically include monthly fees • Does not deal well with micro-climates or site specific performance • Accuracy depends on site-specific input variables
On-site weather station	• Specific on-site weather information • More sensors = more accurate results (temperature, wind, solar, rainfall, etc.) • Reduction in peak and non-peak water use • Can have plant health benefits • Adjust for rapid change or variable weather as seen on site	• Typically require regular maintenance • Accuracy relies on the sensitivity of the sensors, the number of different sensors, and the accuracy of site-specific variables.

Soil Moisture Based Irrigation Control “SMS”

The use of soil moisture sensors to monitor irrigation has been common in Agriculture for over 30 years. A variety of attempts have been made over this period to commercialize automated controls for landscape irrigation with little success.

However, over the last ten years with the growing interest in conservation and water management, new and exciting technical developments have opened a new chapter in soil moisture based irrigation control.

Historically, soil moisture sensors have battled problems such as sensitivity to salts and fertilizers, wear-out or expensive maintenance, or poor performance due to insufficient accuracy or resolution. Modern soil moisture sensors have a whole new level of performance previously unseen performance levels.

Different soil moisture sensors utilize different techniques to measure and utilize volumetric soil moisture content. The table below shows the relative performance of a variety of commercialized techniques for measuring soil moisture content.

For the purposes of this paper, "best" is defined as: "least affected by temperature, salts, fertilizers, and soil composition" as observed in commercially available smart control products as-of the writing of this paper.

Table 7. Relative performance of Common Soil Moisture Measurement Techniques

Best	Time Domain Transmissibility (TDT) Time Domain Reflectometry (TDR) • Least affected by temperature, salts, fertilizers and soil composition
Better	Frequency Domain Reflectometry (FDR) High Frequency Capacitance • Less affected by temperature, salts, fertilizers, and soil composition
Good	Soil Conductivity/Electrical Conductivity Low Frequency Capacitance • Most affected by temperature, salts, fertilizers, and soil composition

A note on these conclusions: Performance of specific commercial products utilizing these techniques can vary greatly, possibly more than the relative strengths or weaknesses of the underlying technique. Additionally, product features are greatly variable between different solutions, further requiring careful review of controller functionality independent of sensor accuracy.

Advanced Watering Using Soil Moisture Sensors

As illustrated elsewhere in this paper, systems utilizing soil moisture sensors can have several distinct advantages over any other commercialized irrigation control solution.

Unique advantages of soil moisture based control systems include:

- Ability to automatically determine soil water holding capacity, including Field Capacity and MAD
- Ability to account for complexities of soil, infiltration, plant fertility and plant nutrition no accounted for in weather based solutions
- Ability to measure true effective rainfall (that which infiltrates to the plant root level)
- Ability to measure true irrigation water penetration in slopes and complex landscapes
- Ability to generate alerts or alarms for irrigators prior to plant damage

Testing of soil moisture based landscape irrigation controllers indicates the following benefits:

Benefits of SMS based irrigation controllers:

- Adjusts automatically for on-site climate conditions
- Reduction in both peak and non-peak water us
- Major plant health benefits
- Adjusts for rapid weather changes

- No maintenance required

Challenges for SMS based irrigation controllers include:
- Discontinuous technology
- Sensor placement & burial required
- Slow detection of rainfall (requires water infiltration into the soil)

Conclusion

It is the conclusion of the author that, properly implemented, soil moisture sensor based landscape irrigation controllers have the proven capacity to provide simpler and more effective landscape irrigation performance improvement than competitive techniques.

By way of analogy, the author asks you to consider a similar energy control system: the modern heating and air conditioning (HVAC) system. In this system, a temperature sensor is used with a simple controller (a thermostat) to control the introduction of heated or cooled air into a home or building.

It is conceivable that the system could be controlled by a simple timer. However, manual override would probably be required on an hourly or sub-hourly basis to achieve effective results. It is also possible that historical weather data could be used to set a heating and cooling program. Likewise, daily or hourly intervention would probably be required for effective results.

Finally, a weather station could be connected to the outside of the building, and a calculation including the “R” factor of the windows, the total BTU’s provided by the furnace, the total cubic feet of each room, etc., could be used to control the system. Clearly, this last option would perform markedly better than the first option. However, it would be more expensive, and provide lower performance than the simple thermostat.

For this reason, and those articulated throughout this white paper, it is the author’s conclusion that soil moisture based solutions, equipped with modern, accurate, and low cost soil moisture sensors will be the preferred method to control landscape irrigation in the near future. History shows that closed-loop control systems, i.e., systems where the performance of the chief variable is directly fed back into the control system, outperform open-loop control systems.

Finally, the author concludes that of all options and alternatives for addressing overwatering as defined in this paper, the introduction of improved control solutions has the potential to provide the most benefit for the lowest actual cost of any alternative option.

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U.S. & Foreign Patents Pending

Understanding Site Conditions and Customer's Perspective When Implementing Smart Irrigation

Irrigation Association
San Antonio, Texas
Irrigation Show
December 2, 2009

Presented By: Loc P. Truong, P.E.

www.Water-Optimizer.com

Overview

- Evaluating Site/Field Conditions
- Critical Factors for Effective Implementation of Smart Irrigation
- Monitoring and Adjustments
- Customer's Perspective/Buy-in By the Customer

Evaluate Site Conditions

1. Geographic Location
    - Florida
    - California
    - Texas
2. Soil Conditions
3. Landscape Type
    - Typical Landscape (turf grass > 60% of landscape)
    - Water Efficient Landscapes (i.e. Florida Water Star Landscape, turfgrass < 60% of landscape)
    - Xeriscape

California

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Florida Water Star Landscaping

Xeriscaping with Plants Native to the Area

California Xeriscaping

Texas SmartScape Gardens

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Critical Factors for Effective Implementation of Smart Irrigation

Considerations:

1. Zone Layout / Uniformity
2. % Coverage/Improper Coverage
   - Repair/relocation of spray heads or rotors may be required
   - Determine Application rates
3. Weather/Climate Conditions
   - Temperature variations
4. Gradient/Slopes in Certain Zones
5. Plant Type/Root Zone
6. Full Sun/Shade Cover

Monitoring and Adjustments

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1. Monitor Landscape
    - Stressed conditions
    - Saturated conditions/Over-watering
2. If soil moisture sensor based system
    - Adjust moisture setpoints
3. If weather based system
    - Adjust parameters (crop coefficients)

Customer's Perspective on Smart Irrigation

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1. Make it Simple/Ease of Use
2. Customer Friendly Installation Guidelines/Support
3. Provide means to easily adjust irrigation controls
   - User friendly interface, Web portal or similar
4. Provide guidance and instructions
   - Operations and maintenance
   - Setting of parameters (crop coefficients, moisture setpoints)
5. Accessible user support "hotline/helpline"
6. Provide means to retrieve data
   - To determine effectiveness of system

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Questions?

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Evaluation of Sensor Based Residential Irrigation Water Application on Homes in Florida

Melissa B. Haley[1] and Michael D. Dukes[2]

Paper presented at the 29th Annual International Irrigation Show
San Antonio, TX
December 2-4, 2009

Abstract

The objective of this project was to determine if an automatic residential irrigation system with soil moisture sensor irrigation controllers could reduce irrigation water application while maintaining acceptable turfgrass quality. Research was conducted on cooperating homes (n=59) in Pinellas County, FL. Experimental treatments evaluated were (1) automatic time based irrigation set and operated by the cooperator, (2) an automatic timer with the integration of a soil moisture sensor, (3) an automatic timer with a rain sensor, and (4) an automatic timer with a rain sensor along with educational materials including a recommended run time schedule given to the cooperator. Continuous irrigation water use, quarterly turf quality ratings, and weather data were collected for the homes over a 26-month period. In addition to elapsed weekly irrigation water use, hourly use was recorded and the fraction of total household use (indoor vs. outdoor) was calculated. The total cumulative savings were calculated compared to the meter only treatment. The soil moisture sensor treatment yielded the greatest savings; with 65% cumulative less water applied for irrigation than the meter only treatment. Although the rain sensor plus educational materials treatment initially showed substantial savings the saving were not as great during the second year of data collection, the total average irrigation savings was 45%. Lastly, the rain sensor treatment yielded a 14% savings over the meter only treatment. These savings trends are similar to what has been found in plot studies.

Introduction

The Florida climate consists of dry and warm weather in spring and fall, coupled with frequent rain events in summer months (NOAA 2003). With these environmental conditions occurring in areas of mostly sandy soil, which has a low water holding capacity, irrigation is often used to supplement rainfall to maintain high quality landscapes. Therefore, automatic in-ground irrigation is common in Florida. Of all new home construction within the United States, more than 15% occurred in Florida from 2005-2006 (USCB 2007). Further, the majority of new homes are sold with automatic in-ground irrigation systems (TBW 2005; Whitcomb 2005). Homes with automatic irrigation systems have been reported to have higher water use compared to manual irrigation or hose-end sprinklers (Mayer et al. 1999).

According to initial plot study results in Florida, soil moisture sensor system controlled irrigation represents a technology that could lead to substantial savings in irrigation water use while maintaining acceptable turf quality, even during dry weather conditions (Cardenas-Lailhacar et al. 2008). The project described here expands the testing of this technology into existing residential irrigation systems as a means to validate the plot study results.

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The objectives of this study were to quantify irrigation water use and to evaluate turf quality differences between: 1) a time-based irrigation system with a soil moisture sensor system, 2) a time-based irrigation system with a rain sensor, and 3) a time-based irrigation system with rain sensor as well as distributed educational materials. All of these experimental treatments consisted of technology or irrigation scheduling intervention and were compared to homes with minimal intervention during the same data collection period.

Materials and Methods

The homes included in this research project were located in the City of Palm Harbor, Pinellas County, Florida within the Pinellas Anclotte Basin of the Southwest Florida Water Management District, SWFWMD (Figure 1). Residential cooperators with automatic in-ground irrigation systems using potable water were recruited. All cooperating homes had a pre-existing automatic irrigation system and time-based controller. Additionally at each home, a positive displacement irrigation sub-meter was installed as well as supplementary equipment (rain sensor or soil moisture sensor) as needed based on participating home treatment type.

Figure 1. Map of the Florida, including location of data collection (Pinellas County).

The homes were divided into four experimental treatments. Treatment classification refers to the method or technology used for irrigation control.

- Treatment one, T1, homes had an Acclima TDT RS-500 soil moisture sensor system (SMS) set at the 10% (volumetric water content) threshold, coupled with the timer-based irrigation controller.
- Treatment two, T2, homes had a mini-click rain sensor (RS) added to the timer-based irrigation controller.

- Treatment three, T3, homes were a comparison group and did not have any control technology other than the existing time clock common to all homes. This treatment is referred to hereafter as meter only (MO).
- Treatment four, T4, homes had a mini-click rain sensor added to the timer-based irrigation system as well as educational materials (EDU).

Research personnel programmed the SMS controller threshold setting, but the homeowner programmed the irrigation time clock. Only in the T4 (EDU) group was an attempt made to explicitly encourage homeowners to set their irrigation timers according to recommended settings after the initial treatment implementation. It is important to note that the MO homes did not have rain sensors.

The primary component of the educational materials included a customized irrigation run time card and documents explaining outdoor water conservation. The run time card is based on the home's specific system design, zone layout, and application rates. This card provides the homeowner with system run times for each season and each irrigation zone. The laminated card was fastened to the controller box. It was hypothesized that the card would make it easy for homeowners to set the correct time on their timer to irrigate a particular irrigation zone.

Four weather stations were setup in Palm Harbor. The stations were relatively close to each other, within 4 km (2.5 miles), and all had a grass reference surface. Each weather station was within a 1 km (0.6 miles) radius of the surrounding homes for the given location. As common with most urban weather stations, the stations were surrounded by different obstacles and encountered different fetch distances. Practical efforts were made to minimize obstructions near the weather stations and the stations were representative of weather data in urban area.

Prior to data collection, an irrigation system evaluation was conducted at each home. During this evaluation any required maintenance resulting from broken heads and/or leaks was noted. Any maintenance that would compromise the irrigation uniformity test was fixed before the testing began. In extreme cases it was recommended that the homeowner fix deficiencies before they could become part of the study. Meter data was used to determine the application rate (depth/time) for each zone on all of the irrigation systems. This information was later utilized when creating the runtime cards for the EDU treatment. An estimation of system low-quarter distribution uniformity (DU_{lq}) was calculated by performing a catch-can test following the Mobile Irrigation Lab Handbook guidelines for Florida (Mickler 1996). Irrigated area was determined based on the Pinellas County property appraisal public records (www.pcpao.org), Pinellas County public GIS records (www.gis.pinellas.org), and the actual irrigation areas were measured at the site visits to homes. The aerial estimated irrigated area was then compared to the calculated irrigated area from the property appraisal information (Haley and Dukes 2007).

Household water consumption, both total household and water used for irrigation only was recorded by flow meter readings. The irrigation water use for the homes was calculated as a depth of water applied (mm or inches) by dividing the volume usage (m^3 or gal) by the irrigated area (m^2 or ft^2) of the home. From July 2006 through April 2007, PCU personnel recorded the weekly elapsed water meter readings manually. Beginning in April 2007, dataloggers were attached onto the irrigation meters to collect actual water use frequency. The dataloggers are part of an automatic meter reading/recording (AMR) technology for data collection using a meter interface unit which attaches to the existing irrigation water meter.

In addition to water use data collection, turf quality ratings were collected seasonally as a benchmark measure of minimum acceptability for each treatment regime. Initial turf quality ratings were taken for each home during the irrigation evaluations, as a baseline standard of comparison for each home. It should be noted that the assessment of turfgrass is a subjective process following the National Turfgrass Evaluation Procedures (Shearman and Morris 1998).

Data analysis was performed using Statistical Analysis System (SAS) software (SAS 2004). The four experimental treatments were replicated at least three times in each of four locations for a minimum of 48 sites. Several treatments had more than three replications for a total of 59 homes in the study group.

Results

Data collection on all of the homes commenced on July 2006 and ended December 2008, with treatments assigned by November 2006 for a total of 26 months. During this period the rainfall was 17% less (1,043 mm) than the historical norm (1,259 mm). A total of 15 of 26 months during the study had less than normal rainfall. August through December 2008 was a continuous dry period.

Over the course of the study, it was observed that the cooperating homes had relatively low water use characteristics. As part of a concurrent study in Pinellas County, response to a mail-out survey was received from 272 homes (including 45 these homes) regarding their irrigating practices. Sixty-nine percent of the these homes reported that they did “consider their irrigation practices to be very water conserving” (Haley and Dukes 2008).

Irrigation application was influenced by the season of the year, as shown in Table 1. The highest water use occurred in the spring months with an average of 56 mm/month applied, compared to the other months with an average of 41 mm/month. The spring months had the highest irrigation demand due to the relatively high evaporative demand as well as low rainfall.

Different irrigation amounts were observed on the treatments depending on study year. Table 2 gives the irrigation application for each treatment for the full study years of 2007 and 2008. In 2007, the SMS and EDU treatments used significantly less irrigation (28 mm/month averaged) compared to the MO and RS treatments (70 mm/month averaged). In contrast, the SMS treatment used the least irrigation in 2008 compared to the other treatments at 19 mm/month. The other irrigation control technologies/strategies used similar amounts of 44 to 54 mm/month (Table 2). Thus, even though the fall of 2008 was dry and resulted in increased irrigation in all treatments (Figure 2), the SMS control systems resulted in significant savings during the rainy summer months as well as intermittent rain in the fall.

Mean cumulative irrigation application for each treatment, over the 26-month data collection period is presented in Figure 2. This figure shows the actual irrigation depth applied by each treatment group, where the recorded volumes were normalized over the irrigated areas. The total cumulative savings were calculated compared to the meter only treatment. The SMS treatment yielded the greatest savings; with 65% less water applied (554 mm) for irrigation than the MO treatment (1,584 mm). Although the EDU treatment initially showed substantial savings, over the 26-month study period the total irrigation savings was 45% with 864 mm applied across the study period. Lastly, the RS treatment yielded a 14% savings over the MO treatment with 1,366 mm applied.

Table 1. Mean monthly irrigation application by treatment for all homes for all study years by season.

Season[Z]	Overall					
	I_{actual}[Y] (mm[W]/month)	N[X] (#)	Range (mm/month)	Median (mm/month)	Std Dev (mm/month)	CV (%)
Spring	56[U]	322	0-950	33	88	154
Summer	37	253	0-264	18	49	133
Fall	45	339	0-572	22	66	146
Winter	40	394	0-577	27	51	127

Note: Uppercase superscript letters indicate footnotes.

[Z] Seasons defined as: spring, March, April, May; summer, June, July, August; fall, September, October, November; winter, December, January, February.

[Y] Monthly average irrigation applied.

[X] N = number of observations in the comparison.

[W] Conversion: 1 inch = 25.4 mm

Table 2. Mean monthly irrigation application by treatment for all homes for years 2007 - 2008.

Treatment[Z]	2007					
	I_{actual}[Y] (mm[W]/month)	N[X] (#)	Range (mm/month)	Median (mm/month)	Std Dev (mm/month)	CV (%)
SMS	27	92	0-309	11	46	165
RS	65	123	0-950	44	119	149
MO	75	122	0-775	38	96	158
EDU	28	101	0-166	22	46	103
	2008					
Treatment	I_{actual} (mm/month)	N (#)	Range (mm/month)	Median (mm/month)	Std (mm/month)	CV (%)
SMS	19	151	0-317	10	60	189
RS	44	137	0-198	39	44	101
MO	54	126	0-241	35	59	109
EDU	47	149	0-372	27	60	130

Note: Uppercase superscript letters indicate footnotes.

[Z] Treatments are: SMS, time-based controller plus soil moisture sensor system; RS, time-based controller plus rain sensor; MO, time-based controller only; EDU, time-based controller plus rain sensor and educational materials.

[Y] Monthly average irrigation applied.

[X] N = number of observations in the comparison.

[W] Conversion: 1 inch = 25.4 mm

These results were similar to what was found in the preliminary plot study. During frequent rainfall conditions, soil moisture sensor savings averaged 72% and during dry weather conditions, savings averaged 28 to 54% (Cardenas-Lailhacar et al. 2008, McCready et al. 2009).

Likewise the rain-sensor treatment resulted in 34% less water applied than the without-rain-sensor treatment during wet weather conditions, and between 13% and 24% during the dry seasons (Cardenas-Lailhacar and Dukes 2008).

Initially it appeared that the EDU treatment was as effective as the SMS treatment, then over time acted more similarly to the RS treatment. Table 2 illustrates similar irrigation between EDU and SMS in 2007 followed by higher irrigation on EDU homes in 2008. A steady increase in the consumptive use of the EDU treatment can be observed beginning in the fall of 2007 (Figure 2). This trend coincides with when the irrigation schedule should have been readjusted back to the lower fall runtime.

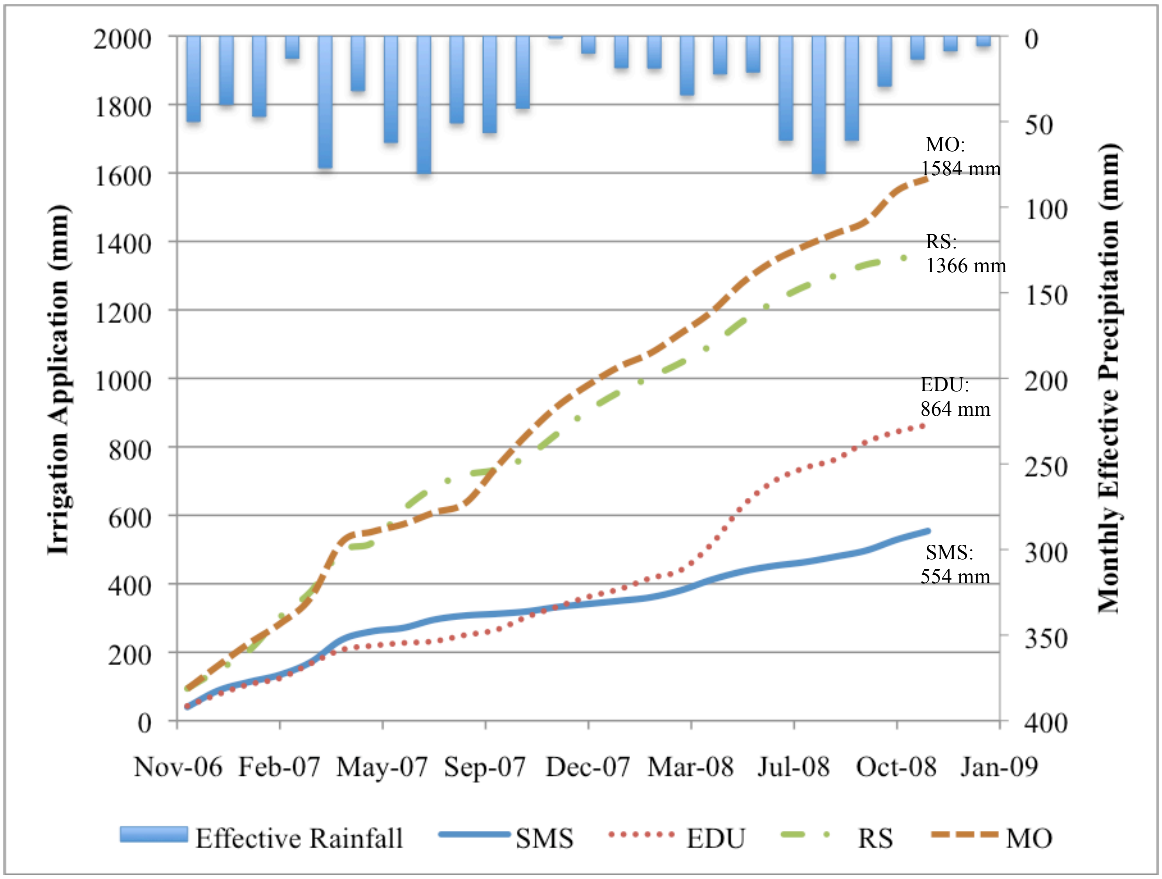

Figure 2. Cumulative irrigation application over the entire data collection period.

Irrigation frequency was determined from the AMR data in addition to volume of water use. Table 3 presents the average monthly number of irrigation events by treatment and season. Analysis of these data yielded an interaction between treatment and location. On average the SMS treatment resulted in 2 events per month, with EDU averaging 4 events, and the RS and MO treatments both with a mean of 5 events per month. Four events per month would agree with the one-day per week watering restriction for the study area.

Table 3 also displays the number of events per season. Since the AMRs were installed during late spring 2007, there was not sufficient data during the spring season to calculate the number of irrigation events, consequently this analysis commenced with summer 2007. The number of irrigation events is shown by season within each year. However, the significant difference between the number of irrigation events and each season only occurred during 2008.

Table 3. Number of irrigation events per month, for the AMR irrigation meter data from study homes during the collection period June 2007 – Dec 2008.

			Number of Irrigation Events					
			I_{actual}[Z] (#[X]/ month)	N[Y] (#)	Range (#/ month)	Median (#/ month)	Std Dev (#/ month)	CV (%)
Treatment[W]		SMS	2.1	185	0-11	1	2.8	136
		RS	4.7	195	0-22	4	5.6	114
		MO	5.2	173	0-29	4	6.5	125
		EDU	3.6	187	0-20	3	4.1	113
Season[V] by Year	2007	Spring	—[U]	—	—	—	—	—
		Summer	2.1	32	0-21	1	4.3	210
		Fall	4.5	81	0-29	3	6.7	153
		Winter	4.1	46	0-21	3	4.9	137
	2008	Spring	5.6	144	0-29	5	5.6	109
		Summer	4.1	138	0-26	3	5.0	135
		Fall	2.8	117	0-20	2	3.6	143
		Winter	3.5	138	0-29	3	4.7[T]	151

Note: Uppercase superscript letters indicate footnotes.

[Z] Monthly average number of irrigation events applied.

[Y] N = number of observations in the comparison.

[X] Conversion: 1 inch = 25.4 mm

[W] Treatments are: SMS, time-based controller plus soil moisture sensor system; RS, time-based controller plus rain sensor; MO, time-based controller only; EDU, time-based controller plus rain sensor and educational materials.

[V] Seasons defined as: spring, March, April, May; summer, June, July, August; fall, September, October, November; winter, December, January, February.

[U] AMRs installed during late Spring 2007.

[T] Winter of 2008 consisted of December 2008 and January 2009 only.

Figures 3 though 6 display examples of the actual water use as collected from the AMR dataloggers for individual homes during a 70-day period. These graphs can visually demonstrate the effectiveness of the sensor functionality. It is important to note that these graphs are depicting individual home examples and not the average of all homes in the treatment. Figure 3 depicts a MO home that is not in compliance with the once per week watering restriction as where Figure 4 depicts a MO home that is in compliance with the local watering restriction. Figure 5 illustrates a home with a functioning rain sensor. It can be seen that although the home is not in compliance with the 1-day per week watering ordinance, the sensor is effectively reducing irrigation events. Finally, Figure 6 presents the water use frequency of a home with a soil moisture sensor.

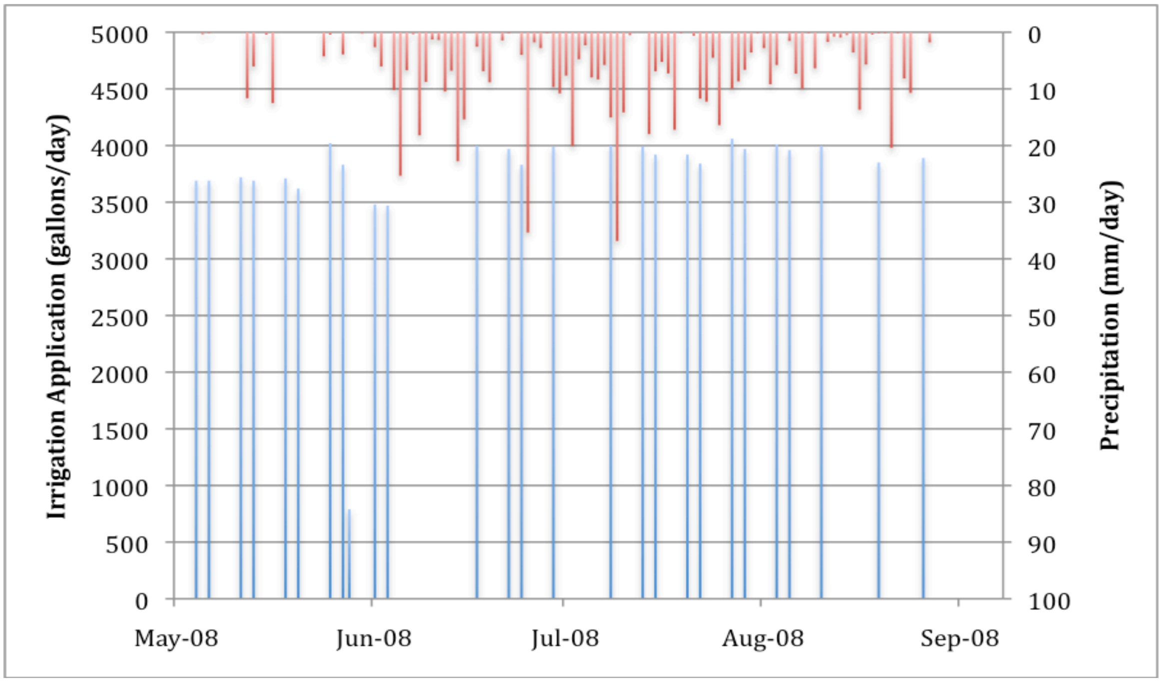

Figure 3. Irrigation frequency of a MO home not in compliance with the 1-day per week ordinace. Blue columns denote irrigation application (gallons/day). Red cloums denote precipitation (mm/day).

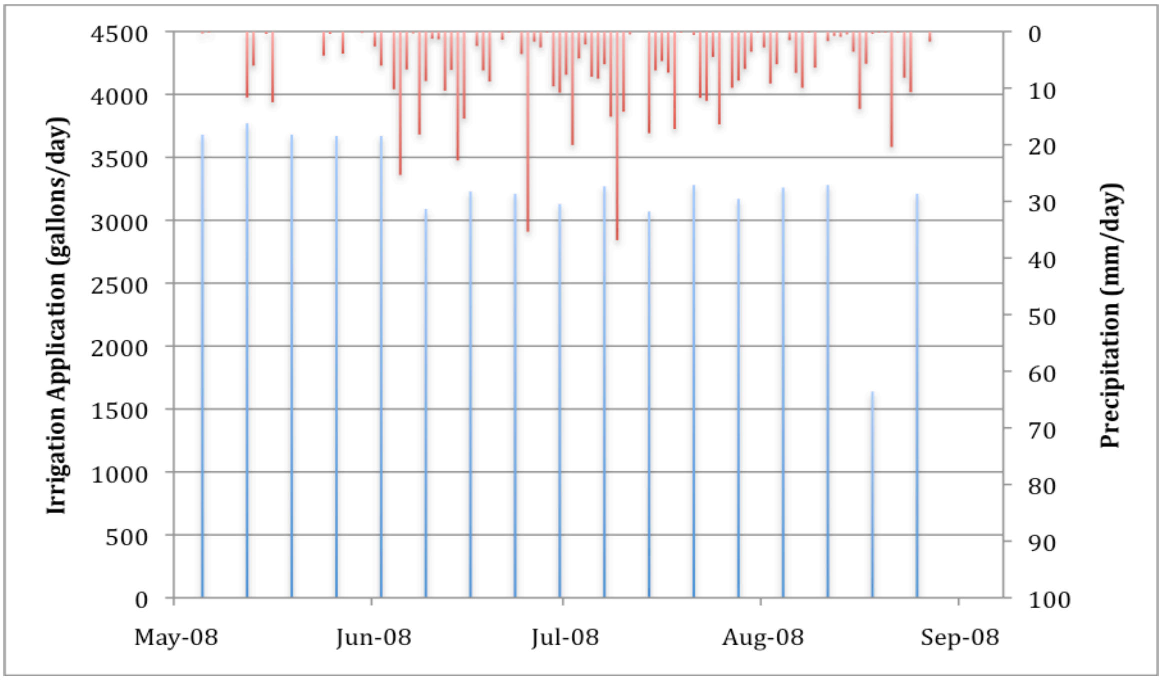

Figure 4. Irrigation frequency of a MO home in compliance with the 1-day per week ordinace. Blue columns denote irrigation application (gallons/day). Red cloums denote precipitation (mm/day).

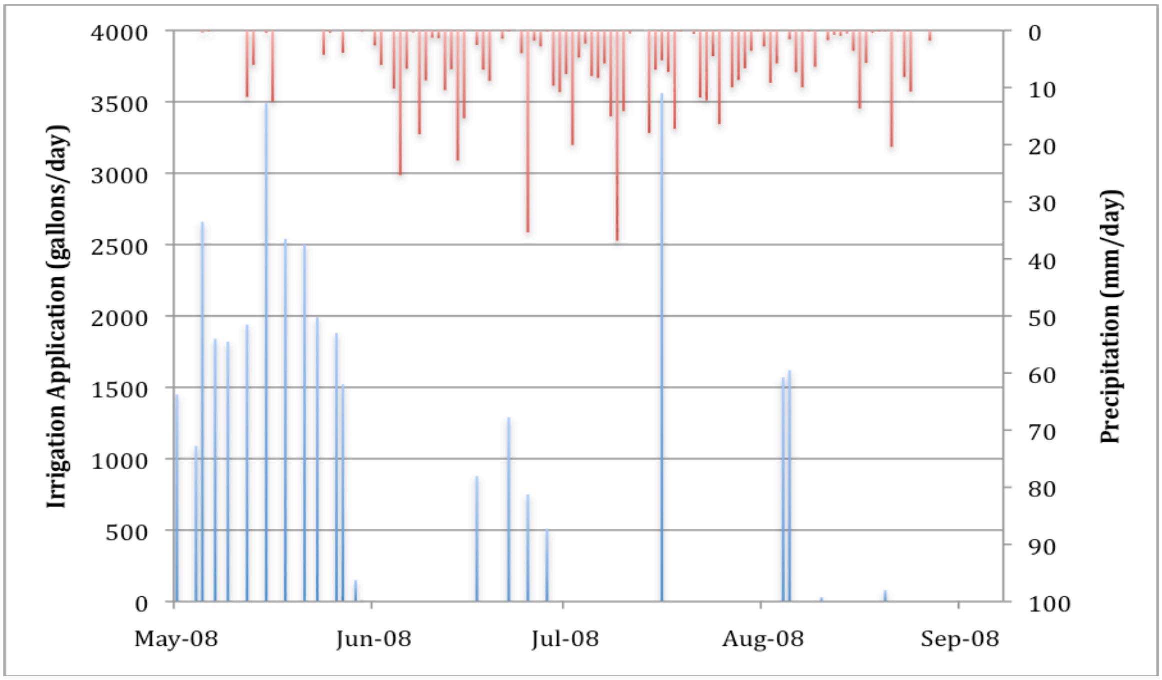

Figure 5. Irrigation frequency of a home with a rain sensor. Blue columns denote irrigation application (gallons/day). Red cloums denote precipitation (mm/day).

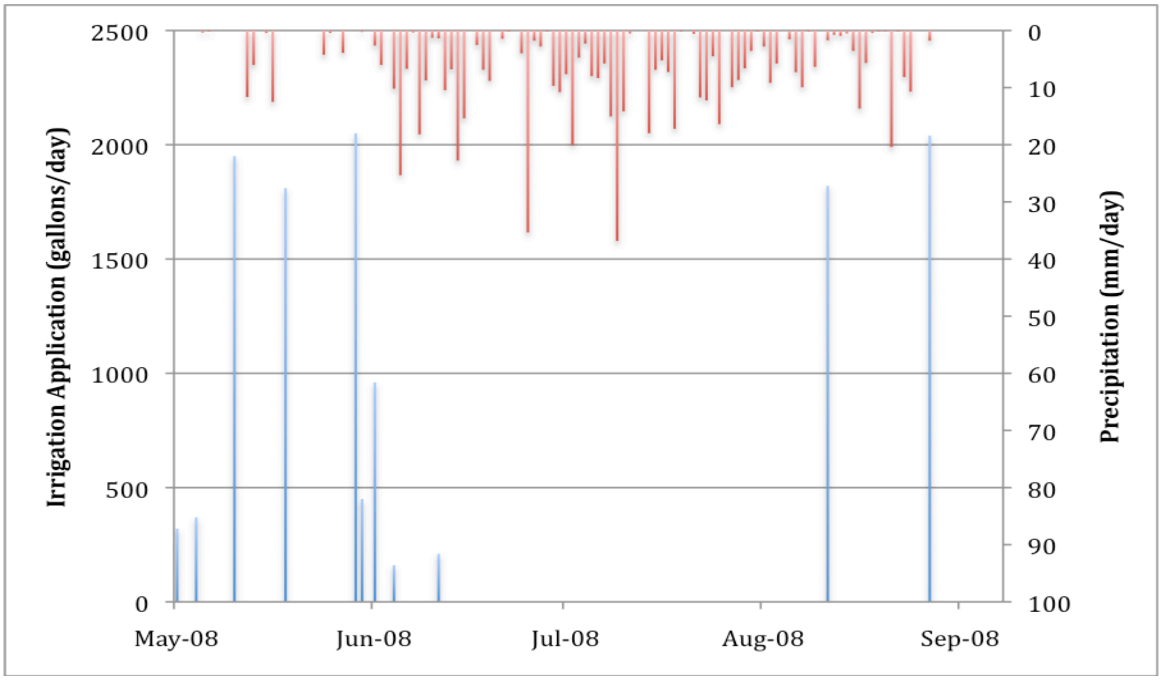

Figure 6. Irrigation frequency of a home with a soil moisture sensor. Blue columns denote irrigation application (gallons/day). Red cloums denote precipitation (mm/day).

Summary and Conclusions

The goal of this study was to quantify irrigation water use between the time-based irrigation system compared to treatments with a soil moisture sensor and controller, rain sensor, and rain sensor along with educational materials advising time clock setting. To determine the treatment effects, the total cumulative savings were compared to the meter only treatment. The soil moisture sensor treatment yielded the greatest savings with 65% of the meter only treatment. Although the educational materials treatment initially showed significant savings similar to soil moisture sensor controllers, over the 26 months, the final irrigation savings was 45%. Lastly, the rain sensor treatment yielded a 14% savings over the meter only treatment. These savings could result a reduction of water consumption up to 262, 189, and 42 gallons per day for the SMS, EDU, and RS respectively compared to homes with no sensor interaction.

Throughout the data collection period, precipitation was 17% less than historical norm. In light of the less than normal precipitation, the soil moisture sensor homes bypassed unneeded irrigation events during rainy as well as dry times with intermittent rainfall, with an average of only 2 irrigation events per month. All other treatments had at least one home more than 20 irrigation events over the course of a month, with a mean of 4-5 events per month. Thus, the soil moisture sensor systems limited the number of irrigation events, where the maximum number of monthly events was 11 versus the 29 events of the meter only treatment. Further, the number of irrigation events by the SMS homes that were half to a third less than the other study homes. Therefore, the soil moisture sensor system controllers can respond as a regulator for irrigation time clock programming that does not correspond to changing weather conditions.

Acknowledgments

This research was supported by: the Pinellas-Anclote Basin Board of the Southwest Water Management District, the Florida Department of Agriculture, and the Florida Nursery Growers and Landscape Association. The authors would like to extend their gratitude to Robert Peacock, Sean Hannigan, Diane Weaver, and Sheryl Powers from the Pinellas County Utilities Conservation Department and from the University of Florida, F. Wayne Williams, Bernard Cardenas-Lailhacar, Mary Shedd McCready, Stacia Davis, Daniel Rutland, Eban Bean, and Kristen Femminella for their assistance and on this project.

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Field Study of Uniformity Improvements from Multi-Stream Rotational Spray Heads and Associated Products

Preliminary Results

Kent Sovocool[1], Mitchell Morgan, and Michael Drinkwine
Southern Nevada Water Authority (SNWA)

10/21/2009

Abstract

Multi-Stream Rotational Spray Heads (MSRSHs) both alone and in combination with other products may offer significant improvements in Lower Quarter Distribution Uniformity (DU_{LQ}). In tentative results from an ongoing study, the authors report that for 97 stations at single-family residences in Southern Nevada, retrofitting traditional fixed pop-up sprays with MSRSHs improved uniformity by 0.18, a relative percent difference (improvement) of 45%.

Additional products tested included a non-rotating, oscillating sprayhead (where a DU_{LQ} improvement of 0.18 was also observed) and in-stem flow control (where an improvement of 0.08 was observed). Combined products stratifications were performed as well with results included below. For all 185 sites covered in this study to date, the DU_{LQ} improvement was 0.16 (relative improvement of 40%).

The results suggest that all the technologies tested do improve DU and in every comparison the results demonstrate statistically significant improvement versus traditional pop-ups. The extent to which water conservation, the ultimate goal for utilities, is practically realized when these improvements are combined with homeowner watering behaviors is still being evaluated at this time.

Introduction

Multi-Stream Rotational Spray Heads (MSRSHs) offer the promise of significant improvements in distribution uniformity and even water savings versus traditional pop-up sprinklers in retrofit applications (Solomon et. al., 2006). Claims of such improvements are invoked because it is believed that such devices are capable of delivering superior uniformity of water application coverage as evidenced by an increase in Lower Quarter Distribution Uniformity (DU_{LQ}) owing to a better

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coverage pattern and a lower application rate. Savings should thus be obtained providing the irrigation schedule is appropriately adjusted to the improvements in the system after retrofits.

There are additional types of products that may lower application and increase uniformity. Some of these, like pressure or flow control, may work in concert with MSRSHs, or function independently to improve distribution uniformity. Some take entirely different approaches to improving uniformity, such as not utilizing a rotational concept at all.

This manuscript covers preliminary results (i.e. after 185 stations thus far completed) from a research study conducted by the Southern Nevada Water Authority (SNWA) that is designed to ultimately quantify the local savings potential of these devices as used in retrofit projects for the single-family residential sector. The preliminary results are expressed principally in terms of change in DU_{LQ} after installation. It is the authors' intent that this preliminary report provide the reader with background to facilitate further discussion and review of the work.

This is not a final or draft final report. The final manuscript will include an even more expansive set of stations and analyses of practical water savings obtained when the behavioral element is considered, recognizing it will take more than a year after installations are completed to effectively evaluate this.

Methods

Interested irrigation component manufactures agreed to provide product to SNWA for purposes of this research study in sufficient quantities that valid statistical testing could be performed for changes in mean DU_{LQ}. SNWA conducted recruitment to the study by way of public messaging, including a web-based sign-up process. More than 450 people rapidly responded for the roughly 200 slots available and were placed on a waiting list before SNWA ended the recruitment. The components evaluated included:

- **Hunter MP Rotators** (predominantly MP 1000s) – a multi-stream rotational spray head.
- **Rain Bird Rotary Nozzles** - a multi-stream rotational spray nozzle.
- **Toro Precision Series Nozzles** – an oscillating-stream spray nozzle.
- **Little Valves** – a user-variable replacement pop-up stem flow reducer (sometimes this product was used in combination with others in specified stratifications).

The research also involves additional stratifications for pressure (including in-head pressure reduction technologies), though these are not addressed in this

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manuscript. While most of the product was donated to the study, SNWA also purchased product, especially to assist in installations such as tools, risers, fittings, etc.

It was communicated to prospective study applicants that in order to qualify a residence needed to have at least 25% of the landscapeable area as turfgrass (this was to assist in successfully being able to partition turf irrigation from future meter data), a working in-ground irrigation system, turf landscaping in decent health, and the participant had to agree to a Participant Agreement governing the terms of the study. The Agreement stipulated among other things that the participant agreed to the installation of product by SNWA staff, that they agreed to maintain their landscape during the study, respond to surveys and requests for follow-up visits, and other reasonable provisions. After installations initiated, SNWA was compelled to also limit participation to properties where spray was not in major ways obstructed (such as by trampolines and the like), where brass heads were not prevalent (the shallow depth associated with these precluded installations of many of the technologies), or where there were other practical concerns. Qualified participants were referred to a trained SNWA team for scheduling of installations.

Pre-installation data collection consisted of recording data about the irrigation controller (make, model, station specific settings, etc.), identifying and documenting turf areas of the landscape, noting slope, and mapping out catchments locations, conducting station pressure and flow tests, and conducting an Irrigation Association (IA) style audit (Irrigation Association 2007, 2009). In some situations where stations were immediately adjacent each other, the stations were effectively treated as a common station for purposes of conducting the audit. In situations where the wind exceeded validity thresholds, the audit and further work had to be rescheduled. Catchments' collection volumes were determined and individually recorded by pouring collected water into a graduated cylinder.

Installation proceeded with retrofit of the heads per the respective technology employed and group assignment. In many cases for practical reasons the heads also needed to be changed out or even moved slightly to accommodate the new technology. Also, there were a significant number of cases in which the throw of water was different post-installation and thus often heads were capped off as no longer necessary. While the stratifications generally determined installed product selections, often the distinct nature of a site (pressure, spacing, etc.) also played a role in what technology was selected for use.

Post-installation procedures began with a check of wind speed (again, if outside the threshold, the audit was postponed). This was followed by a repeat of the audit. Staff were careful to place catchments back in their original mapped locations from the first audit. Root depth was checked as well as the new station water pressure and flow rates.

On-site calculations involved using the catchments' volumes to calculate precipitation rates and DU_{LQ} and to use this to calculate initial runtimes and schedules for residents in a manner analogous to that recommend by the IA as per Certified Landscape Irrigation Auditor (CLIA) training (Irrigation Association, 2009). This schedule was shared with the residents with the caveat that ultimately they might have to deviate from this if they felt conditions dictated adjustments. The residents also filled out a survey covering demographics and other potentially important variables..

Data Analyses and Comparisons

In the office, all data was input to a master database for purposes of the analyses conducted herein and the additional work to come. For purposes of this manuscript, per station audit data was assembled for all stations collected at the time of analyses. Descriptive statistics were collected for the entire set and for each grouping of technologies. The specific groupings and sample sizes analyzed to date were:

- **All Retrofits (*185 stations*)**
- **Hunter MP Rotators (*57 stations*)**
- **Hunter MP Rotators with Little Valves (*26 stations*)**
- **Rain Bird Rotary Nozzles (*40 stations*)**
- **Rain Bird Rotary Nozzles with Little Valves (*25 stations*)**
- **Toro Precision Series (*17 stations*)**
- **Little Valves with Existing Components (*20 stations*)**
- **All Multi-Stream Rotational Spray Heads (*97 stations*)**

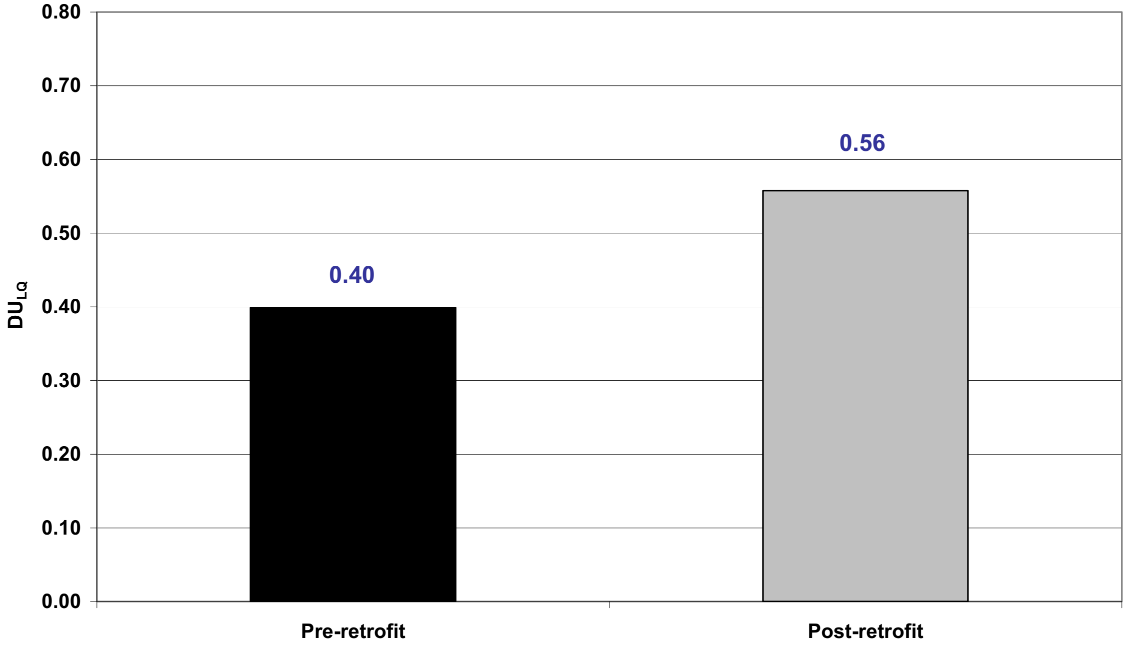
Pre- and post-installation DU_{LQ} measures comparisons were conducted with means. For these tests, standard *T-tests for Dependent Samples* were used to determine if post-installation means were statistically different from pre-installation values. Means testing for inter-group differences in DU_{LQ} were performed using tests appropriate for unequal sample group sizes (*Honest Significant Difference for Unequal N*). In both sets of tests typical default critical levels for accepting means as statistically different.

Results

Entire Sample Results

For all the technologies examined to date, the change in distribution uniformity was 0.16 for the 185 stations that were retrofitted and this change is statistically significant (Figure 1). On average the pre-retrofit DU_{LQ} encountered was 0.40 and the post-retrofit was 0.56. On a relative percent difference basis the average improvement for all sites observed was 40%. It should be noted that as per *Data Analyses and Comparisons*, the selection is unbalanced relative to the groupings.

FIGURE 1: Overall DU_{LQ} Comparison
N = 185, p < .000 (Statisically Significant)



In examining the range of the results, one pattern that emerges is that the percentage change in post-retrofit DU_{LQ} following retrofits seemingly decreases with increasing initial DU_{LQ} (Figure 2). This is especially apparent when comparing the Relative Percent Difference (RPD) in post-retrofit DU_{LQ} (R^2 = 0.701) to starting uniformity (Figure 3).

FIGURE 2: Pre-retrofit DU_{LQ} vs. Post-retrofit DU_{LQ} Improvement Differences

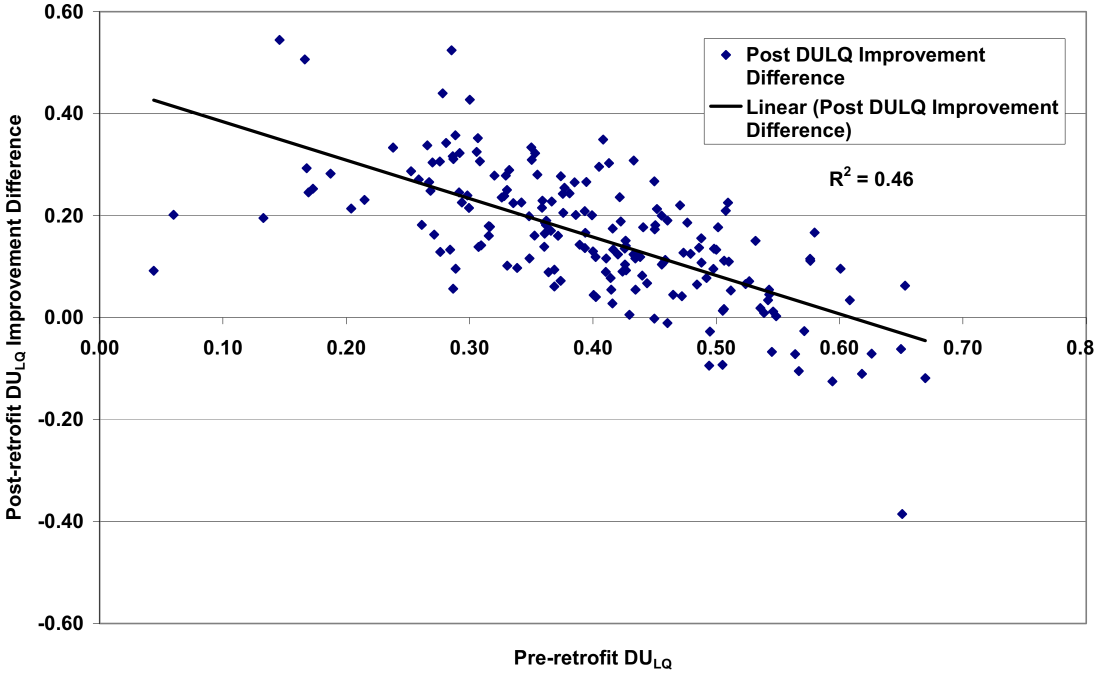
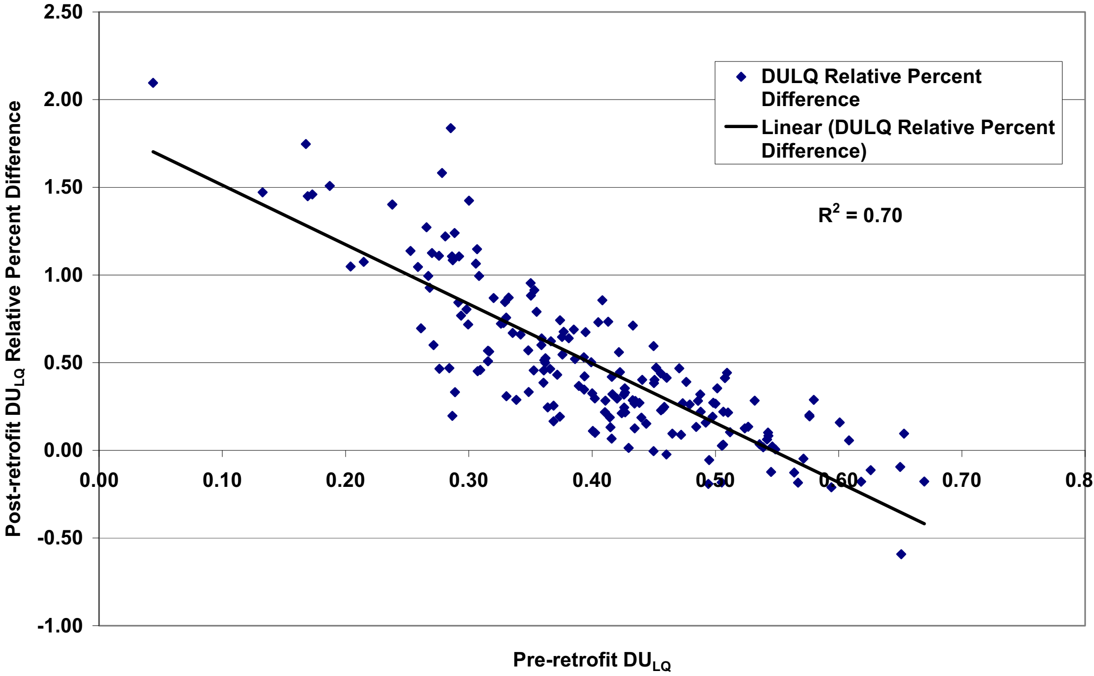


FIGURE 3: Pre-retrofit DU_{LQ} vs. Post-retrofit DU_{LQ} Relative Percent Difference



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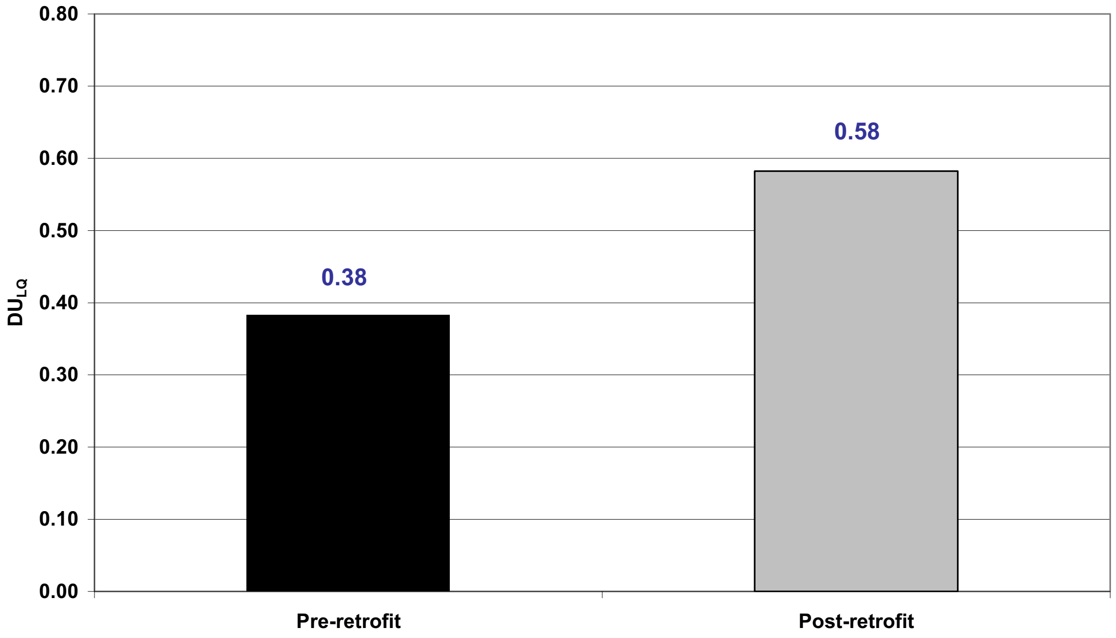
By Treatment Group Results

For all groups, there were no significant differences in pre-installation DU_{LQ} values. In addition to providing reasonable assurance of sufficient sample sizes for the groups, this finding assured that as common as baseline as possible was being used for all *by treatment group* comparisons.

For the Hunter MP Rotators Group (Figure 4), the pre-retrofit average DU_{LQ} encountered was 0.38. Post-retrofit, the average DU_{LQ} was 0.58. The average statistically significant increase in absolute DU_{LQ} was thus 0.20.

FIGURE 4: Hunter MP Rotator DU_{LQ} Comparison
N = 57, p < .000 (Statisically Significant)



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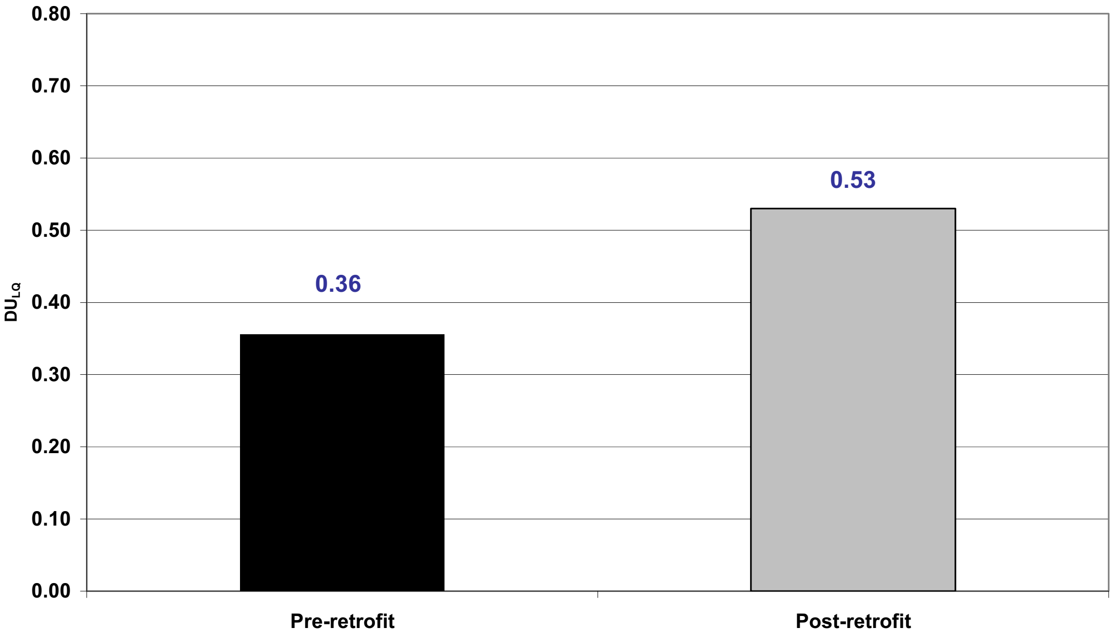
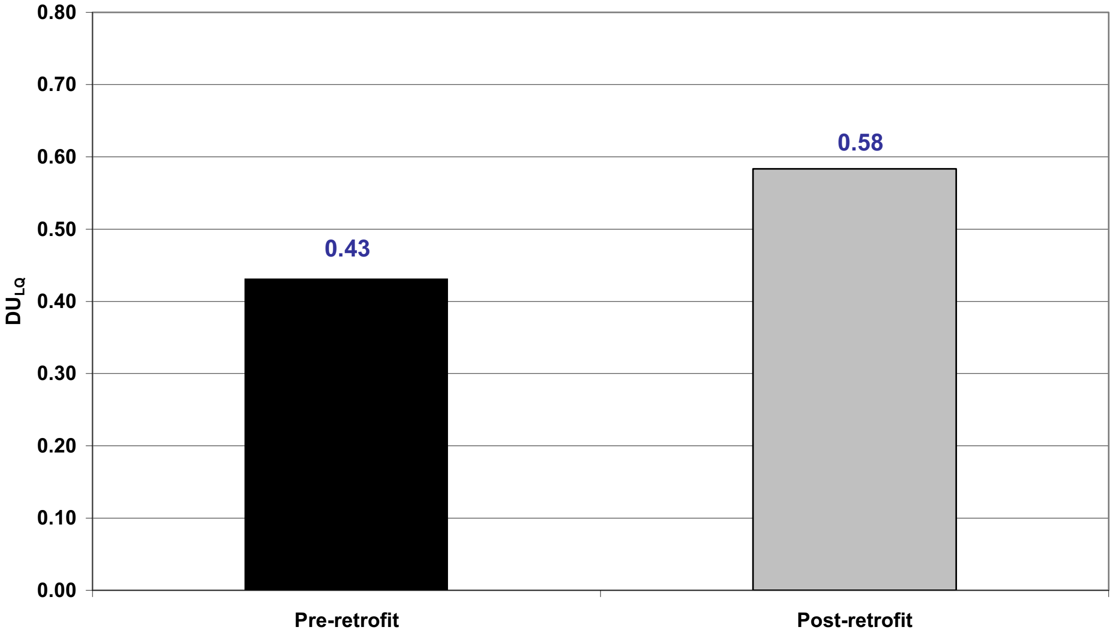
For the Hunter MP Rotators with Little Valves Group (Figure 5), the average pre-retrofit DU_{LQ} encountered was 0.36. Post-retrofit, the average DU_{LQ} was 0.53. The average statistically significant increase in absolute DU_{LQ} was thus 0.17.

FIGURE 5: Hunter MP Rotator with Little Valves DU_{LQ} Comparison
N = 26, p < .000



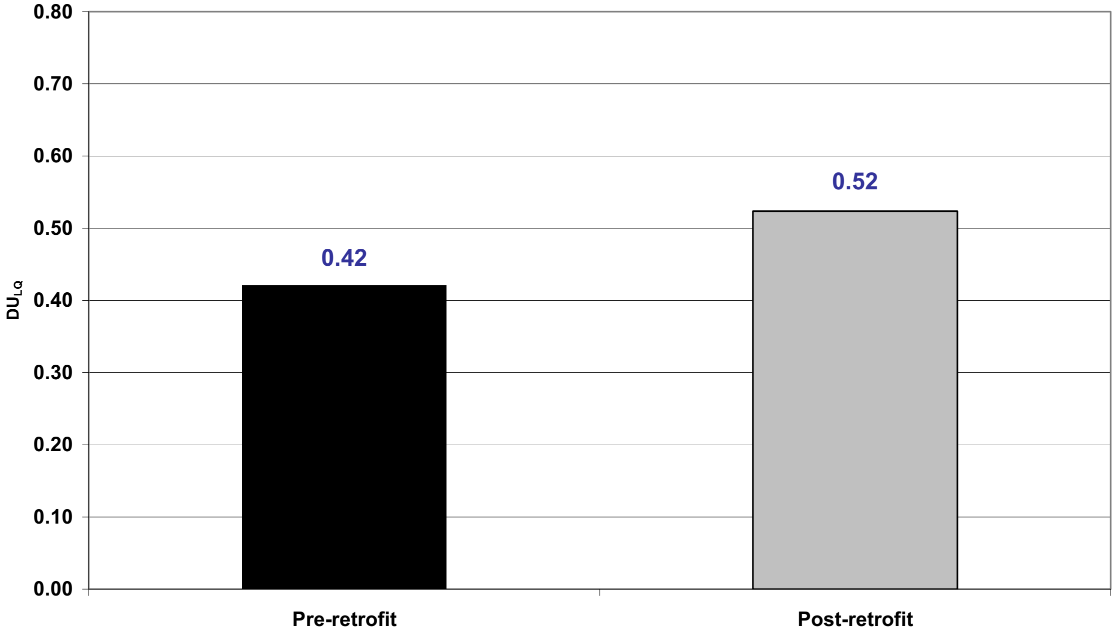
For the Rain Bird Rotary Nozzles Group (Figure 6), the average pre-retrofit DU_{LQ} encountered was 0.43. Post-retrofit, the average DU_{LQ} was 0.58. The average statistically significant increase in absolute DU_{LQ} was thus 0.15.

FIGURE 6: Rain Bird Rotary Nozzles DU_{LQ} Comparison
N = 40, p < .000 (Statisically Significant)



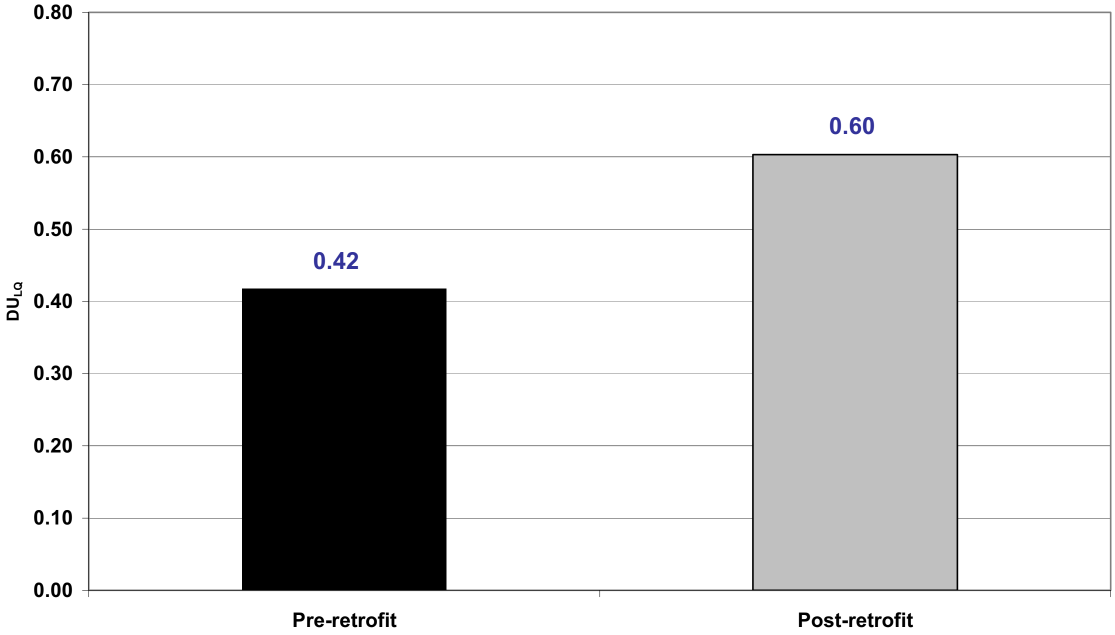
For the Rain Bird Rotary Nozzles with Little Valves Group (Figure 7), the average pre-retrofit DU_{LQ} encountered was 0.42. Post-retrofit, the average DU_{LQ} was 0.52. The average statistically significant increase in absolute DU_{LQ} was thus 0.10.

FIGURE 7: Rain Bird Rotary Nozzles with Little Valves DU_{LQ} Comparison
N = 25, p < .001 (Statisically Significant)



For the Toro Precision Series Group (Figure 8), the average pre-retrofit DU_{LQ} encountered was 0.42. Post-retrofit, the average DU_{LQ} was 0.60. The average statistically significant increase in absolute DU_{LQ} was thus 0.18.

FIGURE 8: Toro Precision DU_{LQ} Comparison
N = 17, p = .000



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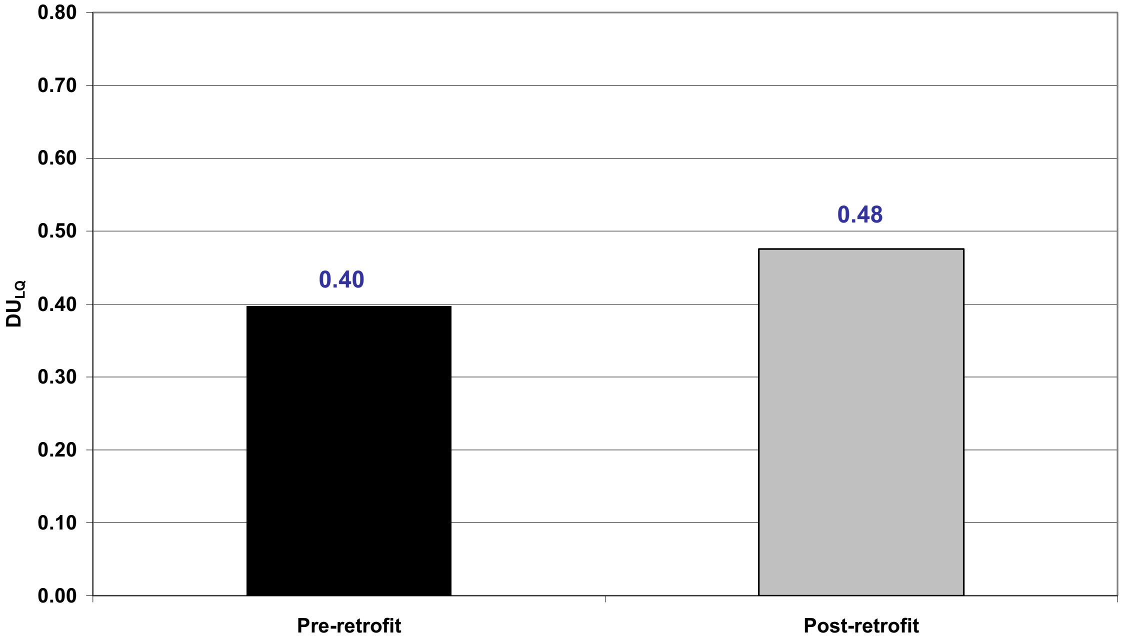
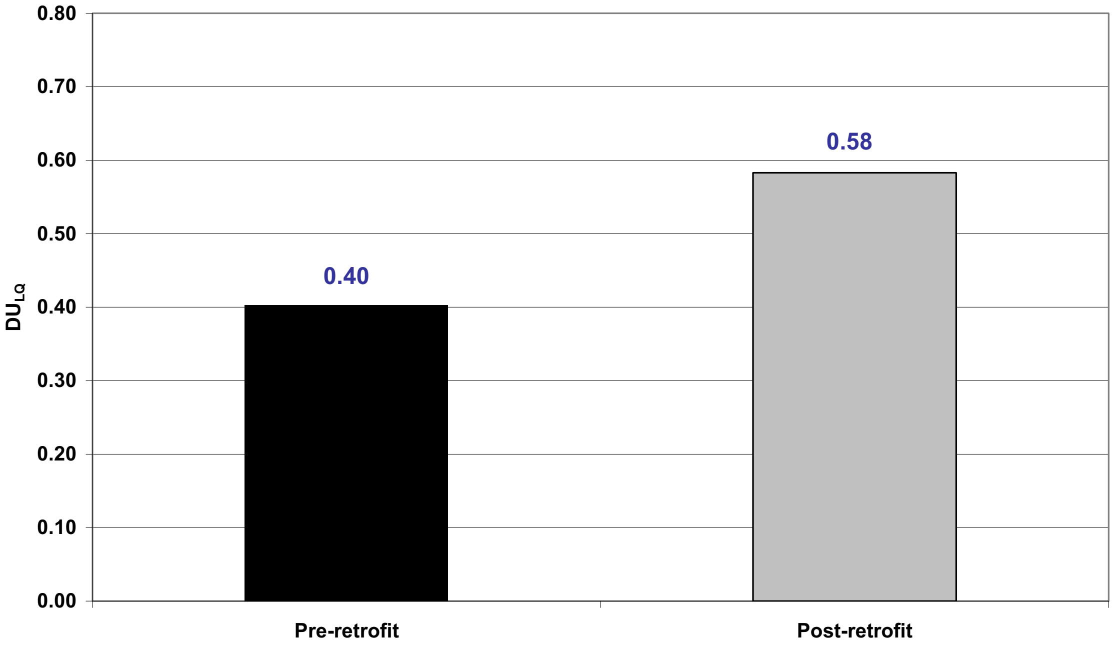
For the Little Valves with Existing Components Group (Figure 9), the average pre-retrofit DU_{LQ} encountered was 0.40. Post-retrofit, the average DU_{LQ} was 0.48. The average statistically significant increase in absolute DU_{LQ} was thus 0.08.

FIGURE 9: Little Valves DU_{LQ} Comparison
N = 20, p < .009 (Statisically Significant)



For the All Multi-Stream Rotational Spray Heads Group (Figure 10), the average pre-retrofit DU_{LQ} encountered was 0.40. Post-retrofit, the average DU_{LQ} was 0.58. The average statistically significant increase in absolute DU_{LQ} was thus of 0.18.

FIGURE 10: All Multi-stream Rotational Spray Heads DU_{LQ} Comparison
N = 97, p < .000 (Statisically Significant)



Discussion and Conclusions

Probably one of the largest, most comprehensive studies of DU_{LQ} was done by Mecham (2004). In this study, fixed sprays in the single-family residential sector averaged about 0.52. Focusing more on the Southwest, Aurasteh (1984) found that in a study in Utah, residential systems could average as low as the sub-0.40 range. In another relatively large study, Pitts and others (1996) determined single-family residential systems in a Northern California city averaged a DU_{LQ} of 0.46. Baum et. al. (2005) found in a study in Florida that fixed sprays had an average DU_{LQ} of 0.41.

In the context of the work here done to date the average pre-retrofit DU_{LQ} of 0.40, while relatively low, is certainly within the range of values seen for residential systems. The focus of this manuscript is though on the change that might be accomplished by relatively easy retrofits to fixed pop-up sprays using available technologies. As mentioned the average improvement in DU_{LQ} was 0.16 or 40%

on a relative percent change basis, taking DU_{LQ} to 0.56, but this is an oversimplification of the dynamics of improvements in uniformity.

For the entire group of properties, as illustrated in Figures 2 and 3 the extent to which DU_{LQ} can practically be improved may well be associated with the initial DU_{LQ} such that the lower the DU_{LQ} pre-retrofit, the more of an improvement the technology may be expected to make. There are of course numerous examples of so called "diminishing returns" in the natural sciences and economic fields. In this case, the results suggest the average DU_{LQ} that can be realized by simple retrofits such as these may not exceed the 50-60% range mainly because this is the point where the diminishing returns nature of the improvements results in RPD essentially reaching zero. Based on the observations, realizing *average* DU_{LQ} values of much more than 0.60 in this area seems unlikely for pop-up sprays in retrofit situations, though of course in some fortuitous *individual* cases such gains can be achieved.

In all of the comparisons above, the improvement in average DU_{LQ} values was significant. For the Multi-Stream Rotational Spray Heads (MSRSHs), whether alone or in combination with the replacement in-stem flow reducers, improvements in DU_{LQ} were realized. Likewise, it should be noted there was no discernable statistical differences in the post-retrofit DU values for the two MSRSH technology using devices. The Hunter MP Rotator and Rain Bird each significantly improved DU to 0.58 and there was no statistical difference between the respective outcomes for the products. For the entire class of MSRSHs, change in DU_{LQ} was 0.18.

The DU improvement realized in this research was unequivocally significant and substantive for MSRSHs. The improvement however did not match with what was predicted in a recent field study (Solomon et. al., 2006). In that study, the predicted average improvement in DU_{LQ} was 0.26. Interestingly though the results are in line with the Farrens data subset that Solomon covered briefly, but did not use in final computations. That subset suggested the improvement in DU_{LQ} was 0.17 which is obviously very close to the 0.18 observed here.

Soloman largely disregarded the Farrens data because it involved in some cases repositioning and elimination of heads (among other issues), explaining that this made the results non-transferable. However, elimination of heads from the authors' observations is often very reasonable given the MSRSHs tend to throw farther than the original installed product (despite the issue, MSRSHs are still the only practical rotors for the range of spacing seen in most single-family residences here). Furthermore, elimination of heads may even be desirable from a water conservation perspective because capping off heads reduces station flow rates. Higher flow rates are associated with greater consumption in the residential sector (Sovocool and Morgan, 2005). Whether or not capping off of heads may have lowered DU_{LQ} in this study in some circumstances, as well as whether a trade-off "cost" in DU versus a benefit in station flow rate reduction is worthwhile, is a topic for further research.

The addition of the Little Valve product to MSRSHs did not result in higher DU_{LQ} values, nor were these statistically lower due to the addition of the device. In practical terms the Little Valve did make installations sometimes more feasible where spacing was closer than the design ranges for the MSRSH products. The Little Valve used alone with whatever existing sprays were encountered was able to raise DU_{LQ} to 0.48, a significant improvement as well. In addition to making installations more practically achievable, it was thought that the addition of the Little Valve could further add to the improvement in DU_{LQ} that was anticipated from the installation of the MSRSHs, but since MSRSHs basically improve DU_{LQ} to the 0.50 to 0.60 range anyway and since this may seemingly be a critical threshold per the above discussion, the concept of "stacking" spray head uniformity improvements in retrofits does not seemingly pan out. The sum of the whole is no greater than the improvement from the part with the greatest DU_{LQ} improvement capability.

The Toro Precision Series product also achieved statistically significant post-retrofit savings with the average post DU_{LQ} reaching 0.60. Although the sample size is small relative to the two MSRSH products (Toro joined the study later than the other groups and delivered limited quantities of product), the initial finding is that the oscillating spray technology is capable of matching the improvements in DU_{LQ} seen for the MSRSHs. An inter-group statistical test of the post-retrofit DU_{LQ} results suggests the improvement from the Precision Series Nozzle is not significantly different from that for either of the MSRSHs, and the improvement in DU_{LQ} of 0.18, again suggests improvements associated with using this product are right on par with MSRSHs.

While the technologies presented here successfully achieved uniformity improvements based on the completed retrofit installations, the question of what practical water savings is obtained in field conditions is still unknown for the sample as of this writing. Solomon et. al. (2006) determined the range of *potential* savings may be between 22% and 40% depending on what runtime multiplier (RTM) is used though this was based on a larger absolute improvement in DU_{LQ}. In that manuscript the authors were appropriately careful to use the term *potential* savings, because in part they no doubt recognize that the behavioral aspect of the irrigator is paramount in mediating the relative success of this, and indeed most other, water conservation projects involving irrigation.

What may be unique about SNWA's study, other than the relatively large field sample, is that it aims in its final form to determine the actual water savings obtained with these systems when homeowner behavioral patterns are included as a dynamic. Homeowners in this study were educated about the devices immediately post-installation (given a custom schedule with RTMs based on their unique system). After this initial education though, the owner will be essentially on-their-own and could stray, thereby impacting savings. In this regards, the study is designed specifically to mimic what might actually occur as utilities incentivize this technology. Whether "straying" would be positive or negative is unknown considering that a failure to follow SNWA's recommended increased run times could actually save more water, though this might be to the detriment of the homeowner's turf quality.

At this time, SNWA anticipates completing the installations in early 2010. At that point the participants will enter a minimum one year monitoring phase to collect data on how they actually use the technologies. At the end of this study, SNWA research staff hope to be able to discover how much these technologies practically do save in Southern Nevada.

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LEED: It’s Not Just Two Irrigation Points

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2009 EPA WaterSense Irrigation Partner of the Year

Background

LEED – Leadership in Energy and Environmental Design is an initiative of the United States Green Building Council (USGBC). Developed in 2001 LEED is a green building rating system. Since its inception, LEED has gained in popularity to the point that it supports a certification and educational system along with the certification of buildings. LEED certifies the following categories of buildings:

New Construction
Core and Shell
Commercial Interiors
Homes
Neighborhood Development
Schools*, Hospitals, Laboratories, Retail

By meeting a minimum number of points, a building can receive a rating of certified, silver, gold or platinum. The higher the rating the more points need to be earned.

LEED 2.2

LEED 2.2, was the third iteration of the original LEED points system, it had a 69-point scale. Categories in which points were earned included Sustainable Sites (14 points), Water Efficiency (5 points), Energy and Atmosphere (17 points), Materials and Resources (13 points), Indoor Environmental Quality (15 points) and Innovative in Design (5 points).

In order to receive certified status, 26 points are required, silver 33 points, gold 39 points and platinum 52 points. The water efficiency category with its five total points available represented 7.25% of the total points, which is small when compared to energy and atmosphere representing almost 25% of the points. Two of the water efficiency points were irrigation related, so irrigation represented 40% of the water efficiency points and 2.9% of the total points available. Moreover, irrigation can contribute to 7.7% (2 of 26) toward LEED-certified status. Not a large percentage, but with LEED all points are important.

The irrigation points consisted of WE1.1 – Water Efficient Landscaping – Reduce potable water use by 50% and WE 1.2 – Water Efficient Landscaping - No Potable Water Use or No Irrigation.

WE1.1 requires the reduction of “potable water consumption for irrigation by 50% from a calculated mid-summer baseline case.” Its intent is to “limit or eliminate the use of potable water or other natural surface or subsurface water resources available on or near the project site, for landscape irrigation." This can be accomplished with a combination of plant material selection, efficient irrigation or the use of alternative water sources. Efficient irrigation technologies should be used which may include rain shut offs, moistures sensors, drip irrigation and smart controllers.

WE1.2 requires that point WE1.1 be achieved and "use only captured rainwater, recycled wastewater, recycled graywater, or water treated and conveyed by a public agency specifically for non potable uses for irrigation" or "install landscaping that does not require permanent irrigation systems." Temporary systems are only allowed for establishment and must be removed within a year of being installed. The intent is to "eliminate the use of potable water, or other natural surface or subsurface water resources available on or near the project site, for landscape irrigation". This can be accomplished by using a non-potable source as mentioned above but also other alternatives such as stormwater, under drainage water and condensate from cooling towers.

There are points available if you do not irrigate as you get both points for no irrigation at all. However, the risk of drought without irrigation in any given year is generally limits the landscaping palette to strictly natives and some adaptive with no turf, so the requirements of Credit WE1.1 still have to be met.

The 50% reduction point is earned by calculating a baseline water use for a project by using conventional plantings and irrigation and then comparing it to the actual design using different plants and more efficient irrigation equipment. LEED provides a template for this calculation and some built in/suggested efficiencies.

LEED 2009

The new LEED 2009 rating system, which became effective in September of this year, is based on a 100-point base scale. Additional points are available for Innovation in Design and Regional Priorities, which is a significant change as they are no really bonus points. Under the new system, certified requires a minimum of 40 points, silver 50 points, gold 60 points and platinum 80 points. LEED 2009 sets a very high bar for the platinum designation. The six categories are now seven and the points have been designated as follows:

Sustainable Sites	26 points
Water Efficiency	10 points
Energy and Atmosphere	35 points
Materials and Resources	14 points
Indoor Environmental Quality	15 points
Innovative in Design	6 points
Regional Priority	4 points

Water efficiency is now worth 10 points or 10% of the overall points available, increasing its importance, but energy is now 35%. Of the 10 water efficiency points, 4 are available for irrigation, still 40% in the overall water category but now worth 4% of the total point's available making irrigation slightly more important than in Version 2.2. In addition, irrigation can contribute to four out of the 40 points (10%) towards the minimum certified level – increasing the importance of efficient irrigation and landscaping practices.

Points are awarded in the same manner as in LEED 2.2 except the 50% reduction of water and non-potable use both are now 2 points. Each credit is now lumped into one Water Efficient Landscaping Credit (as opposed to two sub-credits) for 2-4 points. You can still earn points for no irrigation (4 points).

LEED 2009 also has a prerequisite for a minimum 20% overall building water use reduction. Additional points are awarded for reductions or 30% (2 points), 35% (3 points) and 40% (4 points) overall, but none of these points including the prerequisite can take into account irrigation. Therefore, if you reduced your irrigation water use by more than the required 50%, there would be no additional points under the water efficiency category.

Other Points

Therefore, the water efficiency category is certainly the obvious place to look at earning irrigation points on a LEED project, but irrigation can also play a role in some of the other possible points. One might be Stormwater Design, quantity control. If the stormwater can be directed to the irrigation system, then the quantity of stormwater being released off site will be reduced. Irrigation can also be part of the energy reduction calculations if using alternative sources such as solar panels or other alternative water sources to operate controllers and pumps.

As with any category, points are possible for 'Innovation in Design". These points are very subjective but irrigation can be included. For example, a point might be earned on a park project for providing educational material or displays through the park on how the irrigation system uses alternative water sources and new irrigation technologies to reduce its over all water consumption and explain how much water is being saved. This is an area where out of the box thinking is encouraged. As such, innovative irrigation designs and water supply solutions could be eligible.

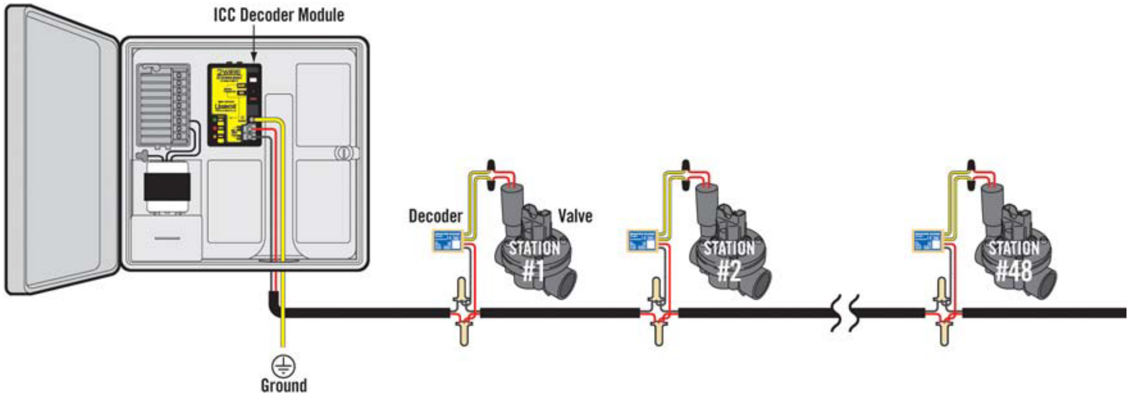
Conclusion

Although the intent and requirements for irrigation points between LEED 2.2 and LEED 2009 have not really changed, the irrigation points do now represent a higher percentage in the LEED certification process. Since all LEED points are important, that is a step in a favorable direction for irrigation. Water efficiency and efficient irrigation systems are an important part of the LEED points system and are a telling example of how irrigation systems are perceived in the "green" and "sustainability" movement.

Fault Tracing Field Wiring Faults in Almost All Decoder systems

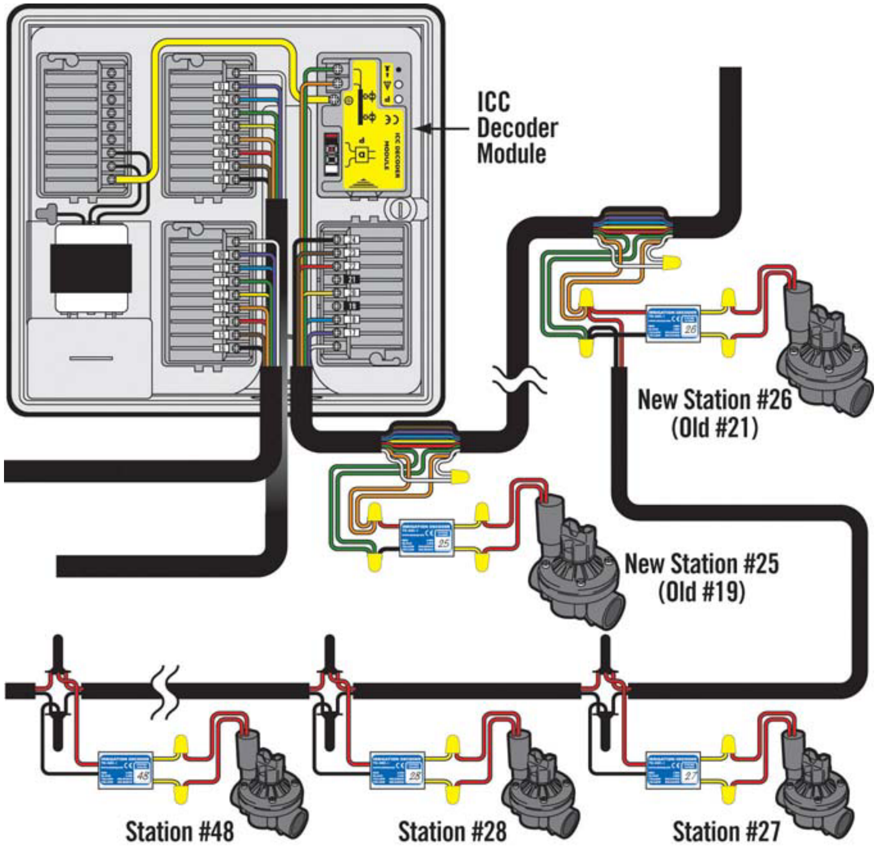
By Tony Ware B.Sc.
Chief Designer,
Underhill International Corporation

Typical 2 wire decoder system



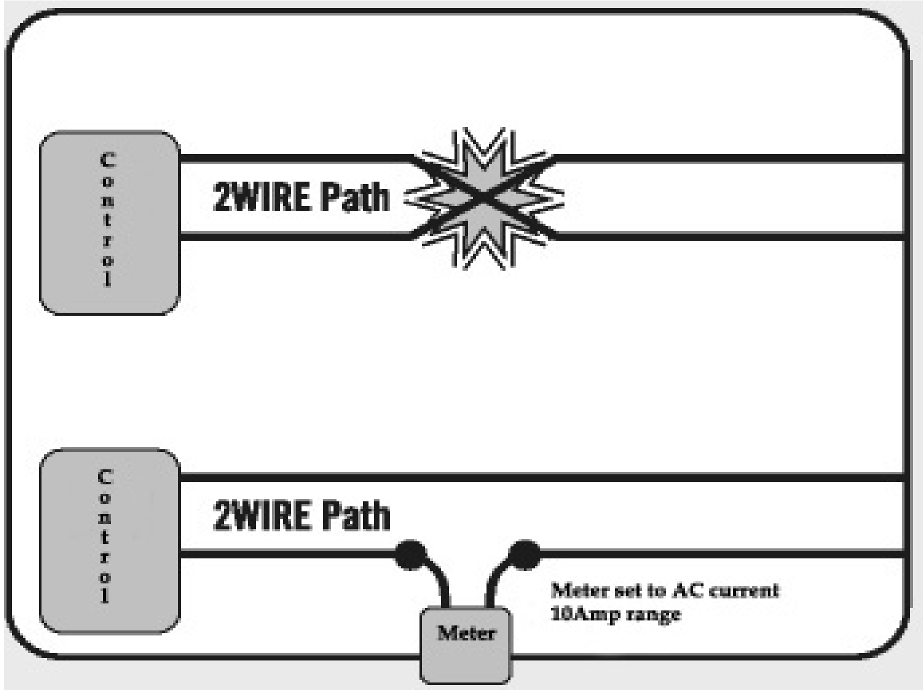
Underhill™

Easy expansion without trenching back to the controller



Short circuit on the main 2 wire path

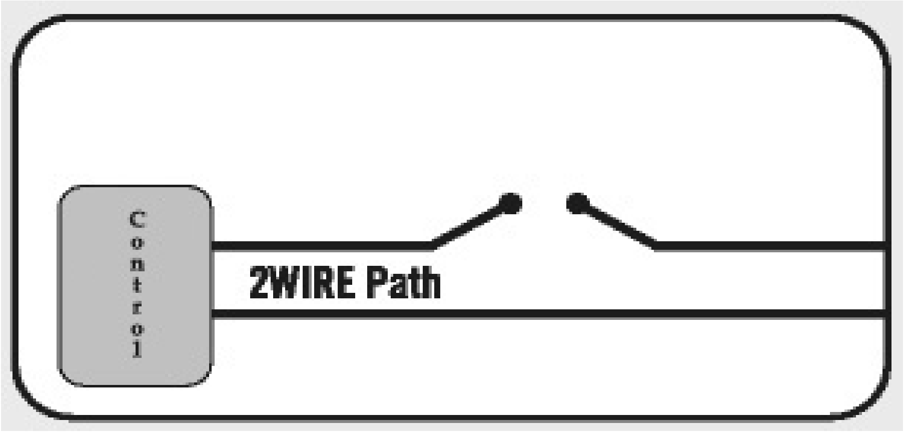
- High currents flow and the controller shuts down to protect itself.
- It is not obvious where the short is.



Meter set to AC current 10Amp range

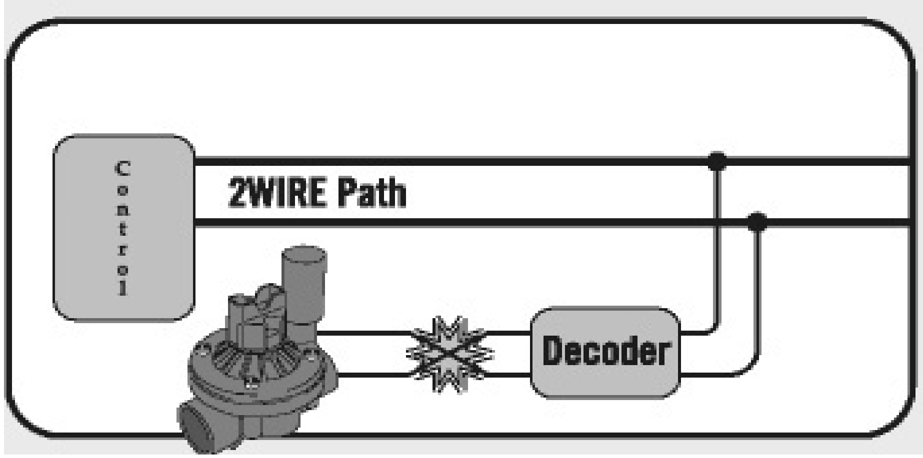
Open circuit in the main 2 wire path

- All decoders up to the open will work, those beyond will not
- Equivalent to a break in the common line in a multi-wire system



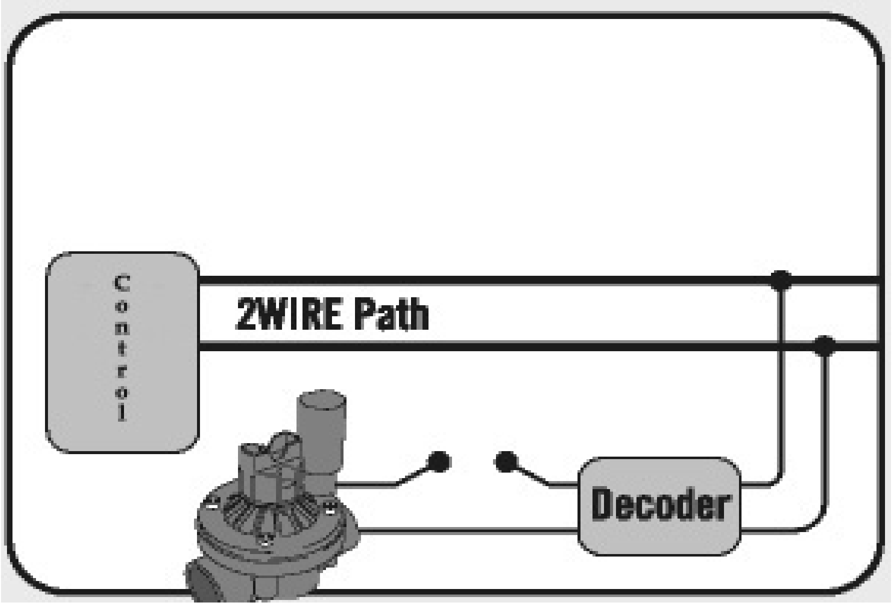
Short circuit solenoid

- Short only shows up when a decoder is operated
- Sometimes stops the system working afterwards due to voltage loss down the main 2 wire path, preventing an off command from reaching the decoder.



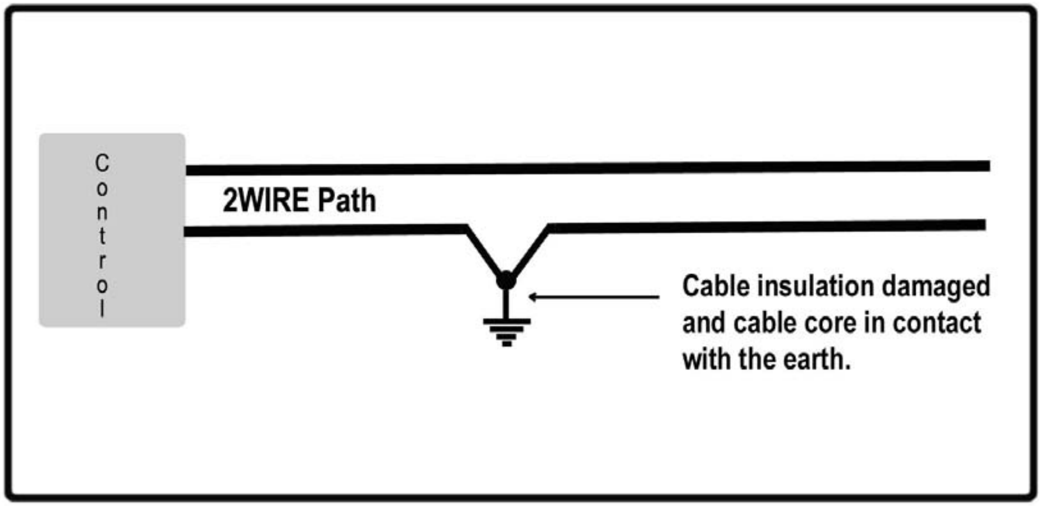
Open circuit solenoid or dead decoder

- Station does not respond
- Can also be a dead decoder



Cable leakage to earth

- When a cable or joint is not well insulated, some electricity can leak to earth. This causes problems for some controllers, either refusing to control at all, or sometimes giving erratic operation, leading to the controller being suspect.
- **Earth leakage must be repaired first** as it can interfere with the diagnosis of other faults.

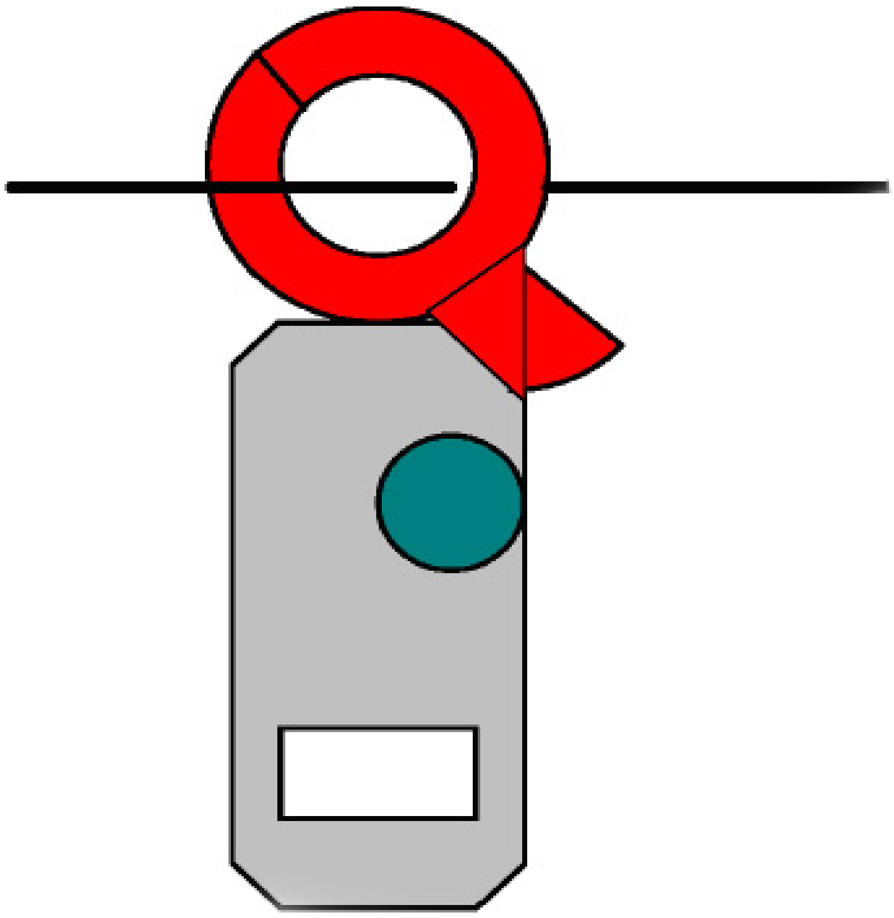


Current Clamp Multimeter

- Single most important tool the fault-finder can own
- To be of use, must be a ‘leakage’ clamp meter. Ordinary ones not sensitive enough

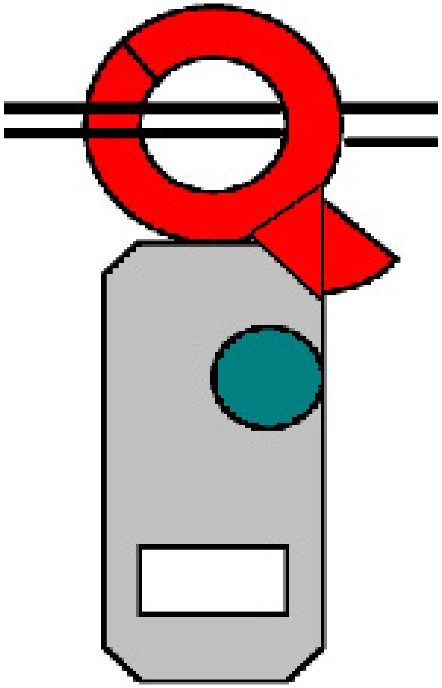
How to measure a current without breaking the wire

- Currents are measured by opening the red jaws by pressing the red trigger with the thumb and clamping the jaws around the wire.



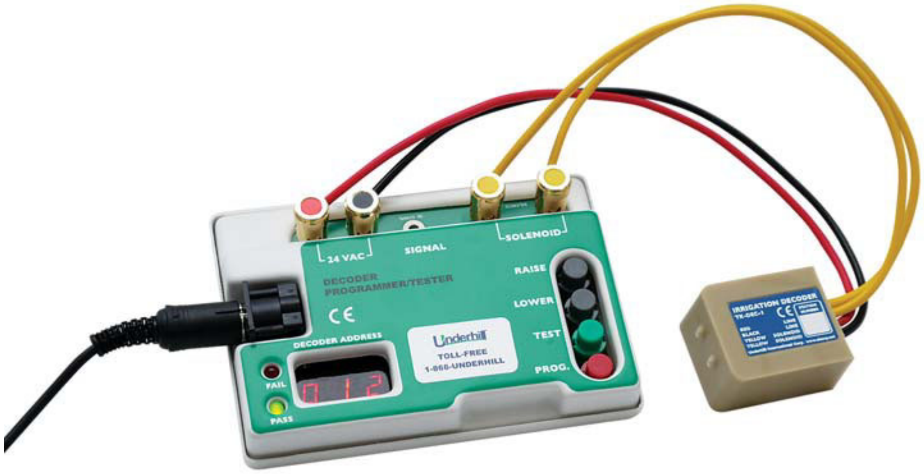
Normally place the clamp around just one of the wires, not both.

- It is important to understand that if both flow and return wires carry the same current and are placed inside the jaws, ***the multimeter will read zero***



Testing a decoder

- All decoder manufacturers offer a decoder tester
- The tester may be used to enter the decoder's station number before installation
- To be of use, the tester has to be low cost or not enough will be available for each crew

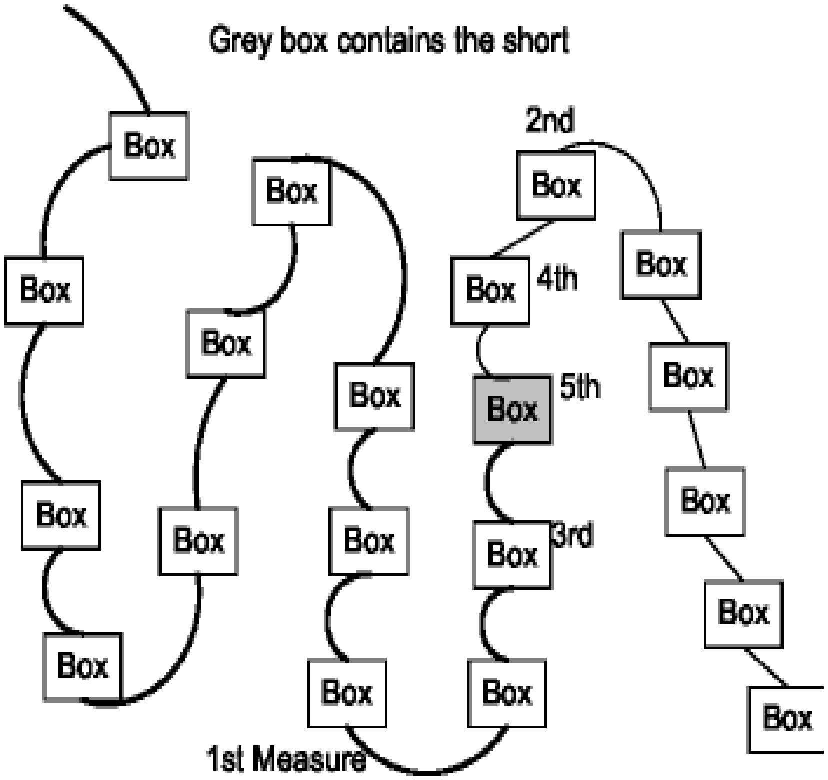


Fault tracing short circuits

- Most controllers will refuse to power up a 2-wire path that has more than a certain amount of load or leakage on it. Fuses may blow, software may shut the cable down, or even worse, a drive transistor in the controller may overheat. If at any time, faults are suspected, or the controller behaves erratically, it is best to test the wiring to the decoders using a power transformer (as illustrated) and a current clamp meter.

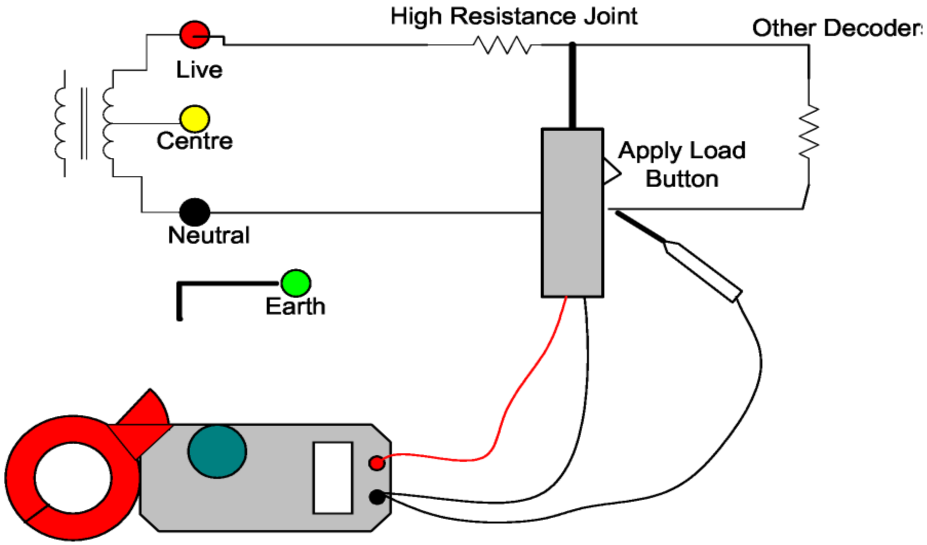
Beyond the short, the current will be much less

- In the figure below, the thick connecting lines indicate higher than normal currents measured. Once you are past the short, the currents will either fall to near zero (if the voltage is cut off downstream) or go back to near normal.
- To measure the short circuit currents, place the current clamp over just one of the 2 wire path wires.



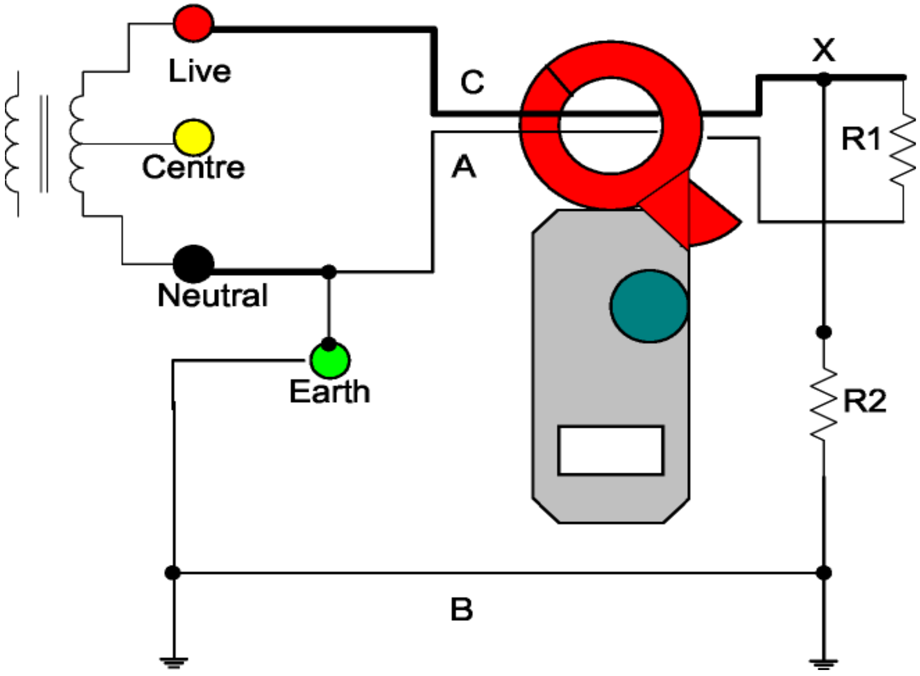
Fault tracing high resistance joints

- Connect the transformer live and neutral to the 2 wire path
- Go halfway down the line, expose the wiring joints
- Measure voltage across the line, with and without a solenoid load
- A volt drop more than 3 or 4 volts under load indicates a high resistance joint upstream.
- Go halfway down the faulty half and repeat
- Using the halving technique you can cover 20 boxes using 5 measurements



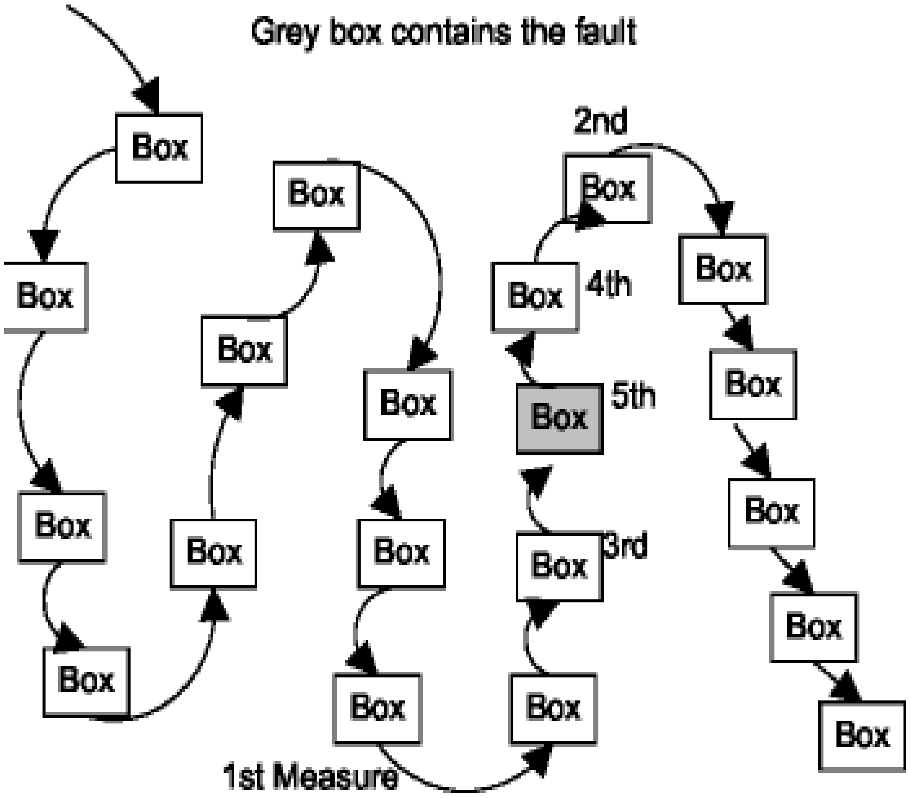
Tracing leakage to earth

- The transformer and the clamp meter can be used to easily find earth leakage. With one side of the transformer earthed, leakage currents can flow back through the ground causing unequal currents in the main 2 wire path.
- In the diagram, point X represents a leakage point to earth through some value of resistance R2. R1 is representative of a quantity of decoders. Current flows 'out' of the transformer through C and splits at X to flow 'back' through A and C. The resistors R1 and R2 are effectively in parallel and see almost all the transformers voltage. The clamp meter will read the difference between the currents in A and C which is equal to that flowing in B.



Finding the location of earth leakage

- The ‘halving procedure’ can be used to minimize the number of measurements made to pinpoint the fault.
- In the diagram, the clamp meter will read much lower when past the grey box.



Phantom Earth Leakage

- When placed over the whole field cable, the current clamp will measure the current imbalance among the conductors. This is caused by some current flowing through the ground back to the transformer (one side of which will be deliberately earthed). However, another reason is cable loops.
- Field cables are sometimes looped and connected back to themselves to lower their resistance, which means less voltage drop when solenoids are on. The currents for the decoder/solenoid can flow in both sides of the loop. If however one wire in one side of the loop is broken or has a high resistance joint, the current in it will favor the good side of the loop. We then have a situation where the total currents when measured in a cable are not equal and opposite. This will show up as a phantom leakage current which can be quite large.
- The **symptoms** are as follows:
  - The 'leakage current' stays substantially the same if the earth connection is removed from the transformer.
- **Resolving the problem**:
  - Break the loop (or loops). After breaking, the good half will have nearly full volts on it, the bad substantially less. If in doubt use the load probe.

The ½ Hour Field Wiring Check

1. Remove the field wires from the controller, connect the transformer instead
2. Measure the 2 wire path’s current with all decoders connected. Does the measured current = the sum of all the decoder currents?
3. Earth one side then the other of the transformer, place clamp meter over the whole cable to measure the total earth leakage. Look for less than 30mA.
4. Go to the far end of the 2 wire path, expose its joints and measure the voltage across it, with and without a solenoid load. A volt drop under load of no more than 3 or 4 volts indicates no bad joints in the main 2 wire path.
5. Tidy up the exposed joints!
6. You may then conclude the whole 2 wire path is good or bad in less than ½ hour!
7. Disconnect the transformer, reconnect the controller.

Conclusions

- If the wiring system passes all the above tests, it is safe to reconnect the controller and proceed with a station decoder test. Obviously for multi 2 wire path controllers, the electrical tests must be repeated for each path. If any test fails, carry out the appropriate faultfinding procedures in the previous sections.
- With these low cost test equipments and simple procedures it is usually possible to clear a fault in less than half a day, sometimes just half an hour.

San Antonio Water System

Lessons Learned from the Introductory Contractor Program

December 2, 2009

2009 Irrigation Association Conference & Exposition

Mark A. Peterson

Project Coordinator - Conservation

Refreshing Ideas

Program Concept

- No current program that focused on the professional sector
- An educational program featuring proactive management, which includes design and maintenance components, to ensure long term **plant health** and **reduce** water usage.
- Not a certification program but work with other professional groups for the participant’s CEU’s
- “Borrow” shamelessly from other successful programs.

A Brief History…

- WaterSaver Landscape Contractor Pilot Program was initiated in 2007
- Initial problems:
  - Continuing drought and attention to regulatory issues delayed start
  - Immediately realized a Technician/Field Worker component was necessary
  - Spent additional time evaluating other successful programs
  - Spent considerable time reaching consensus with disparate groups

A Brief History…

- In 2007,
    - – Created “soft” openings for field staff while discussing professional education
    - – Increase attendance with each successive workshop
    - – Had a waiting list
    - – Instituted recommendations from each event into the next workshop

A Brief History

- In 2008,
  - Reach consensus on Professional and Technician Format, Best Management Practices, and Calendar of Events
  - Held a two day Professional Workshop (14 hours): Regulations, Design, Maintenance, and Irrigation
  - Held four ½ Day Workshops: Planting, Maintenance, Irrigation Design & Regulation, Plant Identification. All with overall emphasis on water conservation
- Results?

Lessons...

- Knew landscapers, irrigators, and landscape architects seldom interacted, but the lack of knowledge was disconcerting.

- Professionals felt two days was too long

- Although attendance was high for ½ Day Workshops (ave.33), companies still felt information provided did not cover their needs or water conservation.

- Designated WaterSaver Landscape Contractors: 3 irrigators, 5 landscapers, 1 landscape architect

Lessons…

- On the whole, irrigators found the information more pertinent than landscapers – “knew plastic but not plants/soil”

- All three professions better understood the importance of site characteristics, design, plant palatte, and <u>scheduling</u>.

- We better understood contractor day to day issues and education deficiencies

- (Personally) Found out that Professional and State requirements for CEU’s differ greatly

Changes…

- Institute a single 6 hour Professional course emphasizing local regulations and technical education (i.e. both plastic & plant) based on Xeric Principles.

- Retain the four ½ Day Workshops but emphasize scheduling, specific pest & maintenance issues (i.e. trouble shoot), plant-soil-water concepts, and plant id.

- Provide examples of WaterSaver Landscape contracts.

- Create irrigation schedule based on site for everyone.

- Retain services of professional trainer to develop state recognized materials for Irrigator CEU's

Estimated Water Savings (cost/benefit analysis)

- Training landscapers and irrigators on efficient irrigation
  - Residential: 3 events/week > 1 event/week
  - Small Commercial: 3 events/week > 2 events/week
  - Large Commercial: 4 events/week > 2 events/week
- Estimated water saved per year: 109 AF
- Next step > follow a sample through year.

San Antonio Water System

Lessons Learned from the Introductory Contractor Program

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2009 Irrigation Association Conference & Exposition

Mark A. Peterson
Project Coordinator - Conservation

In recent years, the focus of the irrigation industry has been on saving water through rotating nozzles and weather based controllers. What about the rest of the system? This presentation aims to highlight conservation opportunities and cost savings associated with less flashy part of the system: pipe, fittings, and check valves.

Sound design at the residential level using low flow nozzles opens up all sorts of opportunities to save on wasting larger pipe and larger fittings. Using check valves adds to the savings in water cost over time.

Pipe

General practice for irrigation design is to use one size pipe for irrigation systems and usually over sized by quite a bit. Yet with todays low flow rotary nozzles smaller pipe can now be used. This conservation design method uses less plastic and saves material costs.

100’ 3/4 SCH 40 PVC BE PIPE	19.78
100’ 1 SCH 40 PVC BE PIPE	28.59

Savings $8.81 or close to a $10 dollar bill

Fittings

The associated smaller fittings are also less in cost and in some cases (1/3 cheaper in price).

1/2 PVC 90 ELL SS	$0.22	quarter	
3/4 PVC 90 ELL SS	$0.33	quarter and a dime	
1 PVC 90 ELL SS	$0.44	2 quarters	

Check valves

PROS-06 HUNTER 6IN POPUP SPRAY	$ 5.78
PROS-06-CV HUNTER 6 IN CHK POP	$7.59

Cost of check valve: $ 1.81

Check valves can dramatically preserve water in the laterals year round, rather than letting the water out of the system each cycle. It is time to start considering the whole irrigation system as an opportunity to conserve!

San Antonio Water System

Backflow Prevention and Irrigation Systems

October 21st 2009

2009 Innovations in Irrigation Conference

Bruce Rathburn
Backflow Prevention Supervisor
San Antonio Water System

Types of Water Services

- Domestic water
- Irrigation/ Landscape
- Recycle/Reclaim
- Fire Protection
- Temporary service

Backflow Protection for High and Low hazards

- Internal isolation
- Internal Containment
- Containment or Premise Isolation

Domestic water

- Drinking water use
- Bathroom use
- Make up water for equipment
- Other uses?

Drinking water

- Water Fountains
- Gang Fountains

Makeup water

- Water heaters
- Boilers
- Heat exchangers
- Cooling Towers

Water heater

- Legionella
- Backpressure
- Thermal expansion

Wa

Boilers

- Scale prevention products
- Back Pressure
- Down stream water lines
- The disappearing backflow preventer

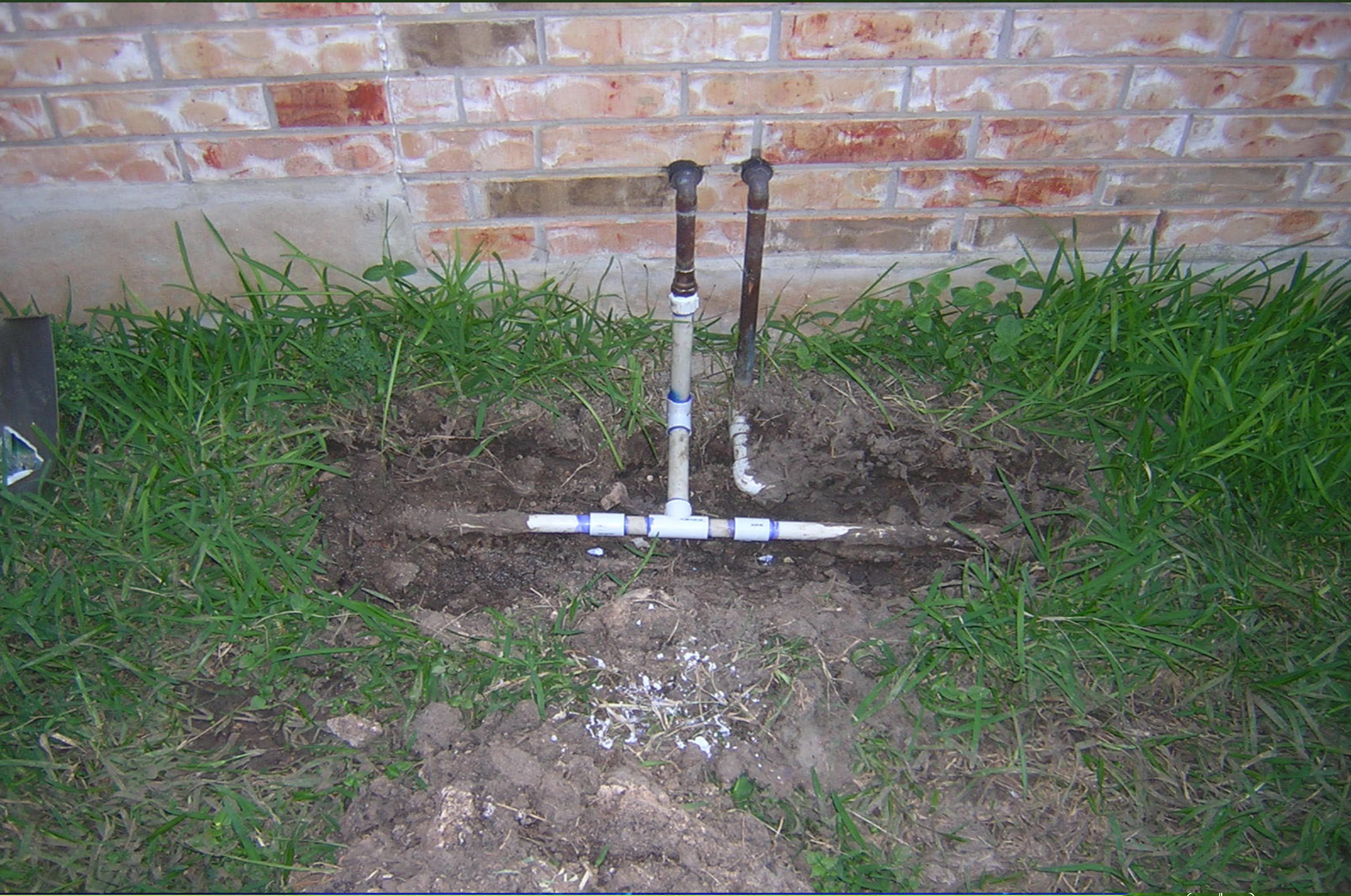

4 11:34 AM

Cooling Towers

- Potable water makeup to basin
- Auxiliary water
- Foaming
- Vapor
- Legionella

Irrigation and Landscape

- Residential
- Commercial



Water Service Connection Types and their Hazards


125
HOUSE
FOR SALE
NEW HOMES
296-5010

Water Service Connection Types and their Hazards

Water Service Connection Types and their Hazards


ED EWALD, INC.

Residential

- Potable water no chemical additive
- Potable water with chemical additive
- Potable water with auxiliary water supply
- Potable water with recycle/reclaim water

Commercial

- Potable water no chemical additive
- Potable water with chemical additive
- Potable water with auxiliary water supply
- Potable water with recycle water

Commercial Sites

- River Authority
- Military Bases and Government Installations
- Parks and Public Golf Courses
- University Campuses
- Private Golf Courses
- Specialty Organizations
- Limited Residential Customers


dream
that li
will one day live
where they will be ju
not by the color of their
skin but by the content
of their hearts
Luther
King


San Antonio Water System
soar
Sports Outdoor And Recreation
The Water Used For The Irrigation At This Site is NOT from the Edward's Aquifer
SAWS has authorized the use of our alternate source of water for irrigation use


QUARRY PARK
San Antonio Water System
soar
Sports Outdoor And Recreation
The Water Used For The Irrigation At This Site is NOT from the Edward's Aquifer
SAWS has authorized the use of our alternate source of water for irrigation use

Recycle

- Tertiary treated water from a treatment plant

- Water from a carwash?
- Cooling Tower blow down?
- Condensate from an A/C?
- Color Coding (purple pantone 512-522)


12 12:03PM


2006 2 24

Reclaimed water

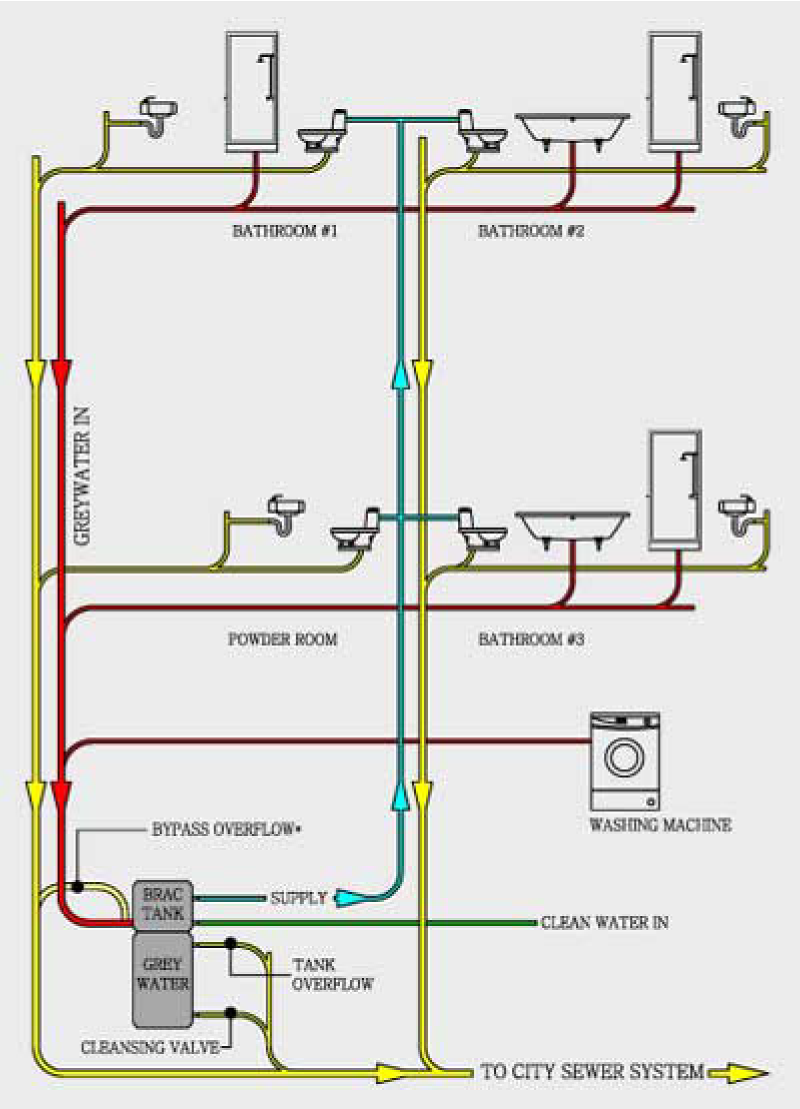
- Rain Harvesting
- Grey Water
- Ground Water
- Color coding (purple pipe)


SEP 8 2006


AUG 28 2006

Rain Harvesting

- On site storage
- Gravity system
- Pump system
- Alternative water makeup (Grey water)
- Color coding (purple pipe?)


BATHROOM #1
BATHROOM #2
GREYWATER IN
POWDER ROOM
BATHROOM #3
WASHING MACHINE
BYPASS OVERFLOW*
BRAC TANK
SUPPLY
CLEAN WATER IN
GREY WATER
TANK OVERFLOW
CLEANSING VALVE
TO CITY SEWER SYSTEM

Grey water

- Washing machine
- Bathroom sinks
- Shower
- Condensate
- Kitchen Sink?
- Dual piping in homes?


WATER RECLAIMED SYSTEM
NON-POTABLE WATER
WATER RECLAIME
NON-POTABLE

GROUND WATER

- During times of heavy rainfall in some areas the ground can saturate to the point the water will channel under the surface
- It can also become artesian and sprout springs up through the ground
- In some instances this can be captured
- Color coding (purple pipe?)

CONTROL
VALVE


700923


4X4
WATER


Aqua-Mate
WATER
(MAY CONTAIN FERTILIZER

Temp Connections

- What is connecting to your distribution system
- How do you track them
- How are your eyes and ears
- Find them in the yellow pages
- Have informative meetings so contractors understand the hazards they create!

Color Code for piping

- Recycle- Purple
- Domestic- Green with White lettering
- Irrigation- Potable Water Yellow Black Lettering
- Rain Harvested- Purple?
- On Site Reclaim- Purple?
- Well- Yellow with Black lettering

San Antonio Water System

Water Service Connection Types and their Hazards

October 21st 2009

2009 Innovations in Irrigation Conference

Bruce Rathburn
Backflow Prevention Supervisor
San Antonio Water System

Water Reduction 101:
An Audit Competition

Innovations in Irrigation
Technical Session
San Antonio, Texas

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Author
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Author
Gordon Kunkle, Hunter Industries, Portland, OR

Abstract

Portland Parks & Recreation Irrigation Services along with our four Service Zones found a way to further reduce water consumption in our park system. Based on past PP&R research, the best water efficiency and related cost savings can be gained by conducting irrigation audits, followed by performing a system tune-up. We have been following the recommendations of the Irrigation Association and the (EPA) Water Sense Program. This involves a combination of training and irrigation system tune-ups.

Each Service Zone group selected a team leader to attend the Irrigation Association Auditor's Course. Following this course, a half day training session was provided by Parks Irrigation Services and local irrigation distributors. It was attended by 30 Park Technicians who learned how to do irrigation system tune-ups. Each of the four Zone teams selected a sports field to analyze. An audit was performed to determine existing system efficiencies. The teams reviewed the data and decided on an improvement strategy. Once the improvements were accomplished, a post-audit was performed to determine the efficiency gains. The winning team went from a 26% DUlq to 63.6%DUlq.

Sponsored by the Portland Water Bureau, each member of the winning team received a Carhartt vest with both Parks & Water Bureau logos. All the teams won in the end by gaining the knowledge and experience to increase the efficiency of the irrigation systems they are responsible for.

Scope of the Portland Parks & Recreation System

There are 247 parks and recreation sites within our system, with over 12,000 acres of land managed by PP&R.
345 full-time employees
1,300 part-time employees
491,757 volunteer hours
1452 acres of turf, maintained on a weekly schedule
A total of 750 irrigated acres

Irrigated park sites are categorized by the type of irrigation systems installed.
1) Automatic Irrigation System. 150 automatic irrigation systems
2) Centrally Controlled. 80 sites on central control
3) Irrigated Park Enterprise Property Golf
4) Well Sites

One of our largest used parks is Waterfront Park located in downtown Portland, hosting a variety of large events throughout the summer. Other facilities include:
102 play structures in parks
115 outdoor tennis courts
7 indoor tennis courts
223 sport fields

Overall Park Management Strategy

Portland Parks and Recreation has developed an action plan that ensures that its staff has the knowledge to use water efficiently, without jeopardizing the integrity of its facilities and programs.

General trends in water management that conserve water:

Innovations and time-tested practices continuously evolve to reduce the PP&R water use while keeping turf and plantings healthy and minimizing impact on the public's safety, use and enjoyment of parks. Some of the water conservation practices PP&R currently employs include:

Irrigation system improvements

Weather data to manage centrally controlled irrigation systems utilizing evapo-transpiration rates

Replacement of inefficient irrigation systems

Refining existing irrigation systems for maximum efficiency

Using well water when available at park sites and golf courses.

Staying current on irrigation technology

<u>Irrigation operational improvements</u>

Performing on-going audits and maintenance for water efficiency on established systems

Education of PP&R staff on good irrigation practices

Utilizing water budget feature of controllers

Adjusting all nozzles to get even precipitation rates

Sharing weekly evapo-transpiration information with PP&R staff

<u>Plant cultural practices leading to water conservation</u>

Mulching plants to reduce water loss

Proper fertilization practices that result in healthy, drought tolerant plants and lawns

Use of more drought tolerant plants

Watering grass deeply to encourage deeper root systems, leading to need for less water

<u>Design and construction standards leading to reduced water use</u>

Shrubs are irrigated separately from lawns

Plants are placed in groupings according to their water requirements

Irrigation zoned for water requirements of plants

Program irrigation controllers to run at optimum times

The Irrigation Section of PP&R has many responsibilities, one of which is being responsible for establishing and actively managing a 'Water Auditing Program' to review and optimize water usage for all irrigated parks. The Irrigation Section is also responsible for the coordination and water management of all Centralized Control Systems as they are implemented.
The Irrigation Section is made up of a Turf & Irrigation Supervisor, five Irrigation specialists and one Horticulturist (Water Manager).

All personnel assigned to IS are trained in water auditing principles, current irrigation theories and technologies, and industry standard construction techniques.

Our PP&R system is divided into 4 Service Zones of Park Technicians, with the Irrigation Section (IS) providing support to all 4 zones. The typical duties of the Park Techs include a full range of grounds maintenance to ensure safety, cleanliness, and the operability of park grounds and facilities. One of their duties is to perform minor repairs and adjustments of irrigation systems as necessary. Our goal is to improve their skills in maintaining their irrigation systems.

A Staffing Imbalance

The one major / significant hurdle is the number of qualified irrigation staff members and the number of irrigated acres.

Irrigation Techs = 5
Park Techs = 30
Number of Parks = 247
Mowed acres = 1450
Irrigated Acres = 750!

The Question:
How to utilize all the resources available to create the most efficient irrigation systems?
A Solution:
Basic Irrigation Training and an Audit Competition

In Summary:

Portland Parks organized an audit competition among the Park Techs, both to train the techs in basic irrigations skills, and to create an awareness of watering efficiency.

The park system is split into 4 work zones. Each team/zone is comprised of 6 members. Each Service Zone group elected a team leader to attend the Irrigation Association Auditor's Course. Following this course, all members from the 4 teams attended basic irrigation troubleshooting and repair classes provided by Irrigation Services staff & local irrigation distributors. All total, 30 Park Technicians attended, learning proper irrigation system tune up procedures. Following the training, each Zone team selected a sports field in their zone to do a pre-audit. A reasonable target goal of a 20% improvement over the current field's distribution uniformity was established. The audits and tune-ups were conducted in the winter months when the staff had the most available time.

Early fall is devoted to shutdowns and leaf removal. Spring is especially busy preparing for summer use. After improvements were made during the tune-up phase, the post-audit was done to determine the winning team. Each team member knew their improvements could get them an embroidered Carhartt vest sponsored by the Portland Water Bureau as a reward for their extra effort!!

Results

Duniway Park	26.7% to 63.6%	+138.2%
Columbia Parks	31.8% to 56.8%	+78.6%
Flavel Park	30.8% to 56.3%	+82.8%
Bloomington Park	39.5% to 49.9%	+24.1%

The park techs were motivated to find ways to increase the irrigation efficiency. As a result, they became familiar with basic irrigation maintenance and tune-ups. They also discovered that efficient watering created healthy turf areas and an overall better appearance of their parks.

Mike Carr C.I.D, C.L.I.A

Portland Parks & Recreation

Turf & Irrigation Supervisor

A Review of IA's New Landscape Auditing Guidelines

Brian E. Vinchesi, CLIA, CGIA, LEED AP

History

In May 2009, the Irrigation Association (IA) released an update of their Auditing Guidelines. The IA originally developed the guidelines "in order to establish uniform, consistent practices" and serve as recommendations in the auditing of landscape irrigation systems. They are not applicable to agricultural auditing (ASABE Standards apply) but are helpful in golf auditing as most of the same concepts apply. A committee of irrigation contractors, consultants and sales personnel with auditing experience began the development of the original auditing guidelines in 2005 and worked on them over a three-year period. In late 2005, there was an open public comment period. In April 2007 the peer reviewed guidelines were first released as "a set of minimum guidelines to provide some degree of standardization of irrigation (auditing) procedures in the irrigation industry." Due to criticism over the last several years that many audits were not repeatable for the same site by different auditors, the guidelines were updated to reflect current best management practices, new research and ASABE standards were incorporated where possible. The revised guidelines were also reviewed by the IA Certification Board.

In September 2009, the guidelines were slightly modified again to reflect the Irrigation Associations decision to report Distribution Uniformity as a decimal as opposed to a percentage.

Basis

Figure 1

Mainstream irrigation audits (Figure 1.) began in the early 80's with the development of the auditing program at Cal Poly San Luis Obispo funded by a grant from the California Department of Water Resources. The passing of AB325 in California required that landscape irrigation systems be audited and as such a large number of individuals attended audit classes and became certified. Experience was not a prerequisite to being certified, although the class was (no longer the case) and still today there are many certified auditors with minimal irrigation or auditing experience. Making a living as an auditor 20 years later has still not come to fruition. Today auditing is once again becoming mainstream, as various regulatory authorities, including the EPA's WaterSense for New Homes Certification program, are requiring audits of new irrigation systems before homeowner occupancy. By following the guidelines, audits on the same irrigation zone should be repeatable and consistent, even if being preformed by different auditors at different times.

Process

Before performing the audit, the irrigation system should be in optimal working order, which may require identifying operational defects and deficiencies. In a pure audit the auditor should also make sure that the system complies with local codes such as backflow prevention devices and water meters or rain shutoffs if required by code or law. However, depending on the purpose of the audit, sometimes the audit should be performed on the system as is. For example, if a system needs to have documented how bad it is operating then you would take the system as you find it.

The auditing procedure is a systematic process. An experienced auditor over time can develop efficiencies in the process that make the audits go faster and therefore make them more economical. Some important auditing points:

1. Maximum allowable wind during an audit should not exceed 5 mph. Wind speed should be monitored and recorded every 5 minutes during the testing portion of the audit.

Figure 2.

Figure 3.

2. The audit should be performed under normal operating conditions, which may be at night when the system usually operates. If it is not performed under normal conditions, a note should be made and assessment of the impact of not being under normal conditions during the test provided.
3. Pressure testing should be done at the beginning and end of each zone audited while the sprinklers are operating (Figure 2.). A static pressure (without sprinklers operating) can also provide useful information.
4. Large catch devices (cups) give better repeatable results (Figure 3.).

5. Location of catchments should be documented. This helps with repeatability.
6. A minimum of 24 catch devices should be used. Smaller sprinkler spacings (less than 15 feet) may require even more catch devices to provide statistical accuracy.
7. Catch devices should be placed 12 to 24 inches from edges.
8. When testing multiple stations, test run times must be adjusted to ensure match precipitation across the test area (i.e. part circles versus full circle zones)
9. Stations can be "linked". By linking, the auditor elects to test one third to one half of the zones to get an average value that can then be applied to other zones that are identical in terms of sprinkler type, nozzling, pressure and spacing.

Test Runtimes

Test runtimes should be based on a minimum volume of water needing to be captured. The volume should be approximately one and one half times the throat area of the catch device. Table 1 shows the minimum amount of water that would be caught for various size catch devices.

Table 1. Minimum Catch Volume Required for Various Sized Catchments

Dimensions	Area	Volume
4" x 5.4"	21.6 square inches	32 ml
4.58" diameter (Cal Poly)	16.5 square inches	25 ml
5.6" x 5.6"	31.36 square inches	47 ml
8.5" x 11.5"	97.75 square inches	147 ml

This will also roughly translate into 5-minutes of run time for sprays and five full rotations for rotary sprinklers. With experience, test times for various sprinkler types, spacings and catch device types become evident.

Catch Device Placement

Along with the number of catch devices, where they are placed is key to having an accurate audit with repeatable results. The placement of the catch devices is dependent on the sprinkler type and spacing as well as what type landscape (i.e. shrubs, small lawn, large lawn, athletic field, green, tee, fairway) is being audited. The auditing guidelines as well as the IA Landscape Irrigation Auditor and Golf Irrigation Auditor Manuals provide specific criteria for placing catch devices based on the sprinkler type and spacings and/or area being irrigated.

- Spray Sprinklers – near a sprinkler and halfway between sprinklers

- Rotors (< 40 foot spacing) – near a sprinkler and every one third distance between sprinklers

- Rotors (>40 foot spacing) – near a sprinkler and one fourth distance between sprinklers

- Irregular shaped areas – a 5 to 8 foot grid spacing for sprays and a 10 to 20 foot grid spacing for rotors
- Athletic Fields – same as >40 or a 20 to 25 foot grid spacing
- Greens, tees, fairways – use a grid spacing, size will vary with the feature and its size (more catch devices needed on a green than on a fairway) (Figure 4.).

Figure 4

Data

For the audit to be complete and be able to perform the required calculations (Lower Quarter Distribution Uniformity and Net Precipitation Rate) all of the following data needs to be collected for each zone audited:

Sprinkler locations
Sprinkler spacing
Sprinkler type including make, model and nozzle
Catch device locations
Catch device throat area
Catchment readings in ml
Test run time
Wind speed-readings
Soil type
Root zone depth
Pressure readings and location
Test date and time
Water meter or flow meter readings if available
Controller type including make, model and features

Since its development, Distribution Uniformity has been presented as a decimal, perfect uniformity being 100%. However, even rainfall is not 100% uniform and for irrigation systems 80% is considered excellent. The problem is that the general public and regulators look at how much lower than 100% irrigation systems are testing and assume that there is huge room for improvement, i.e. much closer to 100%. In order to deter this perfect uniformity concept, the Irrigation Association has decided to calculate and report Distribution Uniformity as a decimal with not comparison to percentage. This is a minor change as Distribution Uniformity has always been calculated as a decimal and converted to a percentage by multiplying by 100. Therefore 0.80 would be considered excellent uniformity with 0.70 being acceptable, etc. This change is not only reflected in the auditing guidelines, but also the IA teaching manuals and class instruction.

Following the proper auditing process will result in an accurate determination of the two measured parameters of an audit: distribution uniformity and net precipitation rate. The results should be repeatable under the same circumstances. Auditing lends credibility to the profession and reduces water use by better scheduling. It is also a lot of fun but you usually get wet, which might not be fun.

The IA provides their auditing guideline “without warranty of obligation”.

Calculation of Uniformity in Landscape Irrigation Auditing

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Abstract

This paper presents a comparison of methods for calculating uniformity in landscape irrigation auditing. The focus of the paper is a the difference between the Christiansen Coefficient of Uniformity (CU) and the Distribution Uniformity of the Low Quarter (DU_{LQ}). For this analysis 236 individual station in 35 sports athletic fields were analyzed. For comparison purposes, the calculations from these same stations are presented using the Distribution Uniformity of the Lower Half (DU_{LH}) and the Coefficient of Variation (CV). For most landscapes, the CU method was found to produce higher efficiency values than the DU_{LQ} method. In some cases, the difference in efficiency between the two methods was as high as 20%.

Background

In 1992-1994, in collaboration with the Irrigation Training and Research Center (ITRC) the irrigation auditing program developed at Cal Poly was adopted to Texas by the Texas AgriLife Extension Service (then Texas Cooperative Extension Service). This program has since evolved into the Texas Landscape Irrigation Auditing and Management (LIAM) Program which includes a two-day, 16-hour training class, training manual, and the Texas Irrigation Auditing and Scheduling Software package. The LIAM program is also supported by the TexasET Network and Website (http://TexasET.tamu.edu). The goal of the LIAM program is to help conserve water through the development and implementation of appropriate irrigation schedules in landscapes, particularly in turf. Since 1995, over 2500 students have completed the auditing program.

Landscape Irrigation Auditing

An irrigation system audit is comprised of performing a catch can test to determine irrigation systems performance and precipitation rate. A catch can test is conducted by placing catch can "devices" in a grid like pattern within an irrigation systems station. Multiple cans are utilized per station but the number will vary based on the sprinkler spacing and the number of heads in the station. Once the cans are in place, the irrigation system is turned on. After a brief amount of time, usually between 8 and 15 minutes or until there is a readable volume in each can, the system is turned off. The volumes collected are then recorded (either in milliliters or inches). In auditing, this data is then analyzed to assist in determining seasonal irrigation schedules, runtimes for individual stations, and distribution uniformity estimates of the system.

Texas Landscape Irrigation Auditing and Scheduling Software package continues to evolve based on input from users and changes in auditing procedures. The software allows auditors to enter their catch can volumes per station into the software, along with site specific data such as root zone depth, soil and plant type, adjustment factor, MAD, etc. The software includes historical ETo from 19 cities which is used along with the audit data to produce the irrigation schedules. Once all data is entered, a station statistical report can be generated. This report displays the stations precipitation rate, distribution uniformity (low quarter method, DU_{LQ}) and the coefficient of uniformity (Christensens, CU). The base irrigation schedule can then be generated. The software allows users the option of including average rainfall in the schedule. While the software allows users to adjust the runtimes based on either DU or CU, our recommendations are to not do this which is the default setting of the software.

SAFE Program

The LIAM program is an important component of the SAFE (Sports Athletic Field Education Program) which is conducted by the Texas AgriLife Extension Service. The purpose of the SAFE program is to educate managers of sports fields on proper turf, nutrient, and chemical, and water management in order to promote quality facilities while conserving water and protecting the environment. Over 100 facility managers have participated in this program which includes an audit of their fields. Types of fields used in this study include but are not limited to Football, Soccer, Baseball and Softball Fields (McAfee, 2009). Thirty-five (35) of these sites with a total of 236 stations from the SAFE program are used in this paper to examine DU calculations.

Uniformity Methods

The Distribution Uniformity (DU) varies in landscape irrigation systems based on several factors, including the design of the system, the type of sprinkler equipment used, and installation and maintenance practices. Baum, et al. (2005) used DU as an indicator in a comparison of rotor and spray residential irrigation systems. In this University of Florida study, 25 residential systems were audited. In comparing the CU and DU_{LQ} values for residential systems, the averages were 59% and 45% for rotors and sprays, respectively , and that the CU method consistently produced higher DU efficiencies . While rotors had higher DU_{LQ} than spray heads, the authors reported that all the DU_{LQ} results were lower than what should be expected. (Baum, et al., 2005).

Lower Quarter Distribution Uniformity

Various methods exist to determine the DU of an irrigation system. The method widely used in irrigation auditing is the Low Quarter Distribution Uniformity Method (DU_{LQ}). This method can be calculated as follows:

$$DU_{LQ} = \frac{\bar{V}_{LQ}}{\bar{V}} \quad \text{(Eq. 1)}$$

Where $\bar{V}_{LQ}$ is the average volume of the lowest quarter of the cans and $\bar{V}$ is the average of all the cans. This method places more emphasis on the adequacy of irrigation among the low quarter of catch cans. In ranking the irrigation volumes from lowest to highest, this method neglects the overall location of the irrigation water applied and not taking into account any beneficial (high volumes) that may have been applied near the low volumes (Zoldoske and Solomon, 1988).

Christiansen's Coefficient of Uniformity

While not widely used landscape irrigation, CU is the most widely accepted and used method for calculating the uniformity efficiency of irrigation systems. Christiansen's Coefficient of Uniformity (CU) takes a different approach to evaluating system performance. By taking the absolute value of the irrigation volume from the mean (the standard deviation), the method treats over irrigating and under irrigating equally:

$$CU = 1 - \frac{\sum_{i=1}^{n} |Vi - \bar{V}|}{\sum_{i=1}^{n} V_i} \quad \text{(Eq. 2)}$$

Where V_i is an individual catch cans volume and $\bar{V}$ is the mean (average) catch can volume. In comparing the standard deviation to the mean, you calculate on average how uniform the irrigation is being applied (Zoldoske and Solomon, 1988).

Low Half Distribution Uniformity Method

In recent years, another method to calculate uniformity of the irrigation system has been proposed, the Low Half Distribution Uniformity Method (DU_{LH}). In order to calculate the DU_{LH}, the DU_{LQ} is required (IA, 2005). This method is calculated using the following equation:

$$DU_{LH} = 38.6 + (0.614 \times DU_{LQ}\%) \quad \text{(Eq. 3)}$$

Coefficient of Variation

The Coefficient of Variation (CV) is a uniformity measure that has been used to characterize the uniformity of drip irrigation products. This method can be calculated by dividing the standard deviation of the catch cans by the overall mean catch can volume (Dukes 2006). The formula is shown below:

$$CV = \frac{\sqrt{\frac{(V_i-\bar{V})^2+(V_{i+1}-\bar{V})^2+\cdots+(V_N-\bar{V})^2}{N}}}{\bar{V}} \qquad \text{(Eq. 4)}$$

Typically CV is a unit less value expressed as a decimal. CV values that are closer to zero indicate less variation between data values whereas values closer to one show a greater variance in the data. For the purposes of this study, CV shows how similar one catch cans volume is to another's in the station.

Analysis and Discussion

The audit data from 236 stations from the SAFE Program was input into a spreadsheet (Microsoft Excel) to calculate the uniformity values from Equations 1-4. The results are summarized in Tables 1-3 and Figures 1-3 below. CV values were subtracted from 1 (100%) to depict data on the same standard as other methods (normally low CV value indicate less variation-greater uniformity).

DULQ Rating Scale

The Irrigation Association has developed a rating scale for evaluating low quarter distribution uniformity (IA, 2005). Table 1 shows this rating scale for rotors. Table 2 shows the number of stations with DU which fell within each rating scale class. For the irrigation stations analyzed in this study, the largest percentage (48%) of the low quarter distribution uniformities would fall in the "Very Poor" (< 40%) category whereas less than 15% of the CU values calculated for the same stations would be classified as "Very Poor".

Table 1. Rating of Lower Quarter Distribution Uniformity for Sprinkler Zones (IA, 2005)

Sprinkler	Excellent %	Very Good %	Good %	Fair %	Poor %
Rotor	80	70	65	60	50

Table 2. Number of Stations Per Rating and Uniformity Method

Rating	DU_{LQ}	DU_{LH}	CU	1-CV
Excellent > 80%	3	29	12	7
Very Good 70-79%	18	89	46	21
Good 65-69%	10	42	42	20
Fair 60-64%	24	40	42	27
Poor 50-59%	67	35	59	71
Very Poor < 49%	114	1	35	90

Figure 1 shows the DU calculations for all stations. A linear distribution was calculated for the different methods and the R Squared Value reported in Table 3. Figure 2 and Figure 3 show the DU for same stations at a Football and Baseball Field.

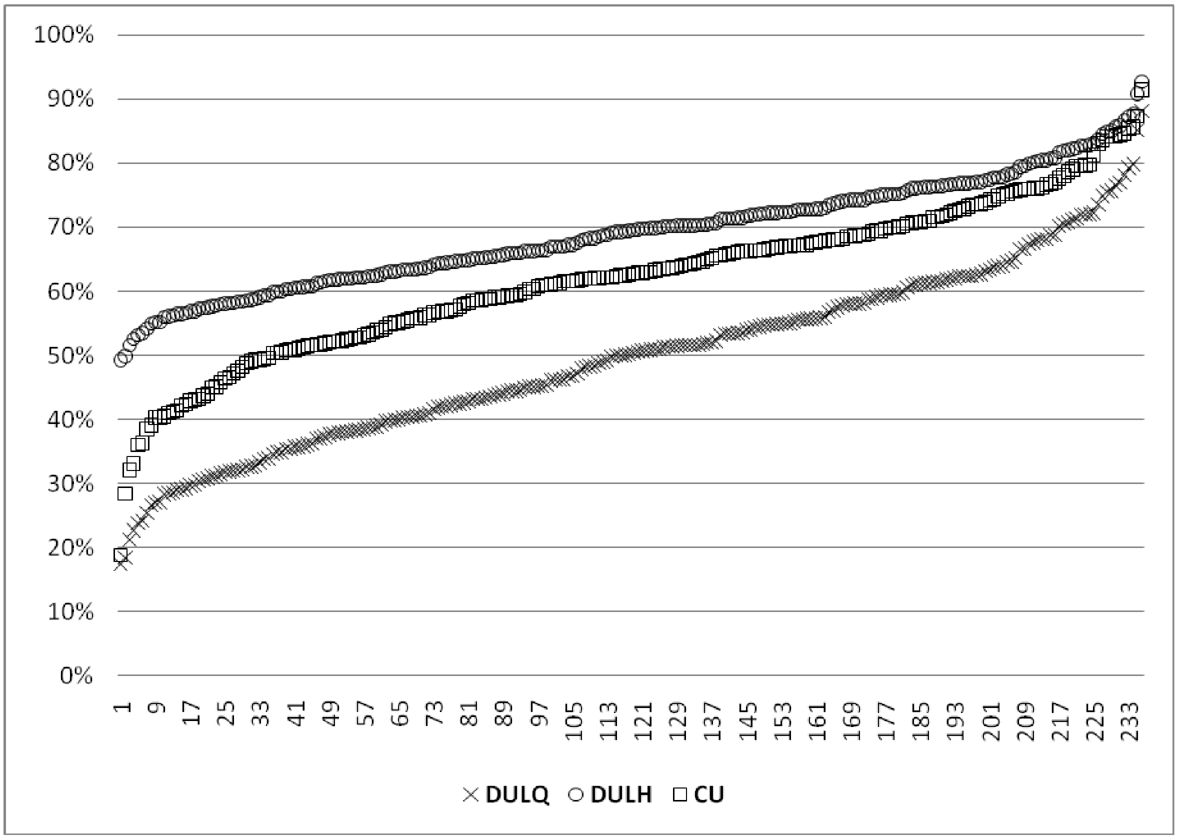

Figure 1. Comparison of Uniformity Values

Table 3 shows the mean, standard deviation and other common statistical analysis of the average DU calculated by each method. The DULQ method produced the lowest uniformity values of all methods. Statistically the DULH method produced the highest uniformity values of the methods.

Table 3. Uniformity Analysis of Different Methods, 236 Stations

Method	DU_{LQ}	DU_{LH}	CU	1-CV
Mean	50%	69%	62%	52%
Standard Deviation	14.2%	8.7%	12.2%	16.6%
Median	50.3%	69.5%	62.7%	45.6%
Max	88%	93%	91%	91%
Min	17%	49%	19%	1%
R Squared*	.9606	.9606	.9303	.9199
Average Cans Per Station: 17				

*R Square Calculated Using a Linear Distribution

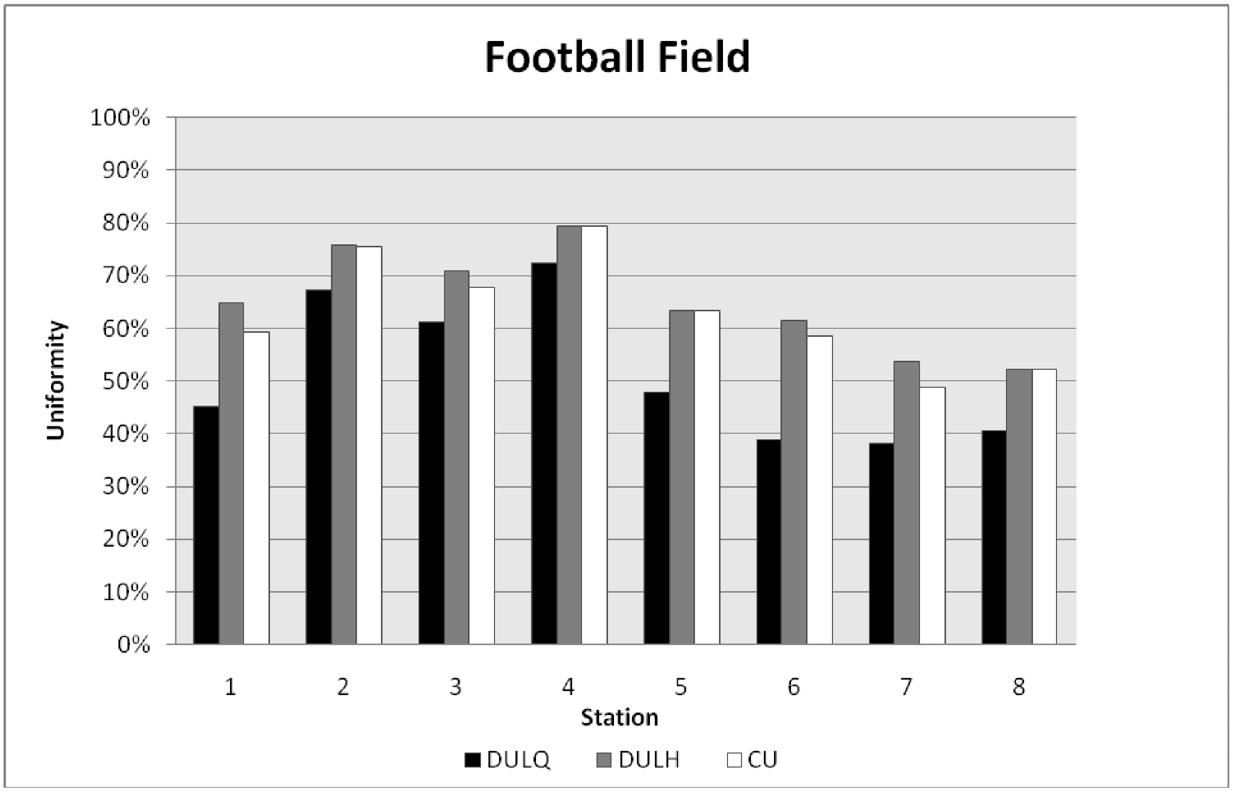

Figure 2. Comparison of Uniformity Values for a Football Field

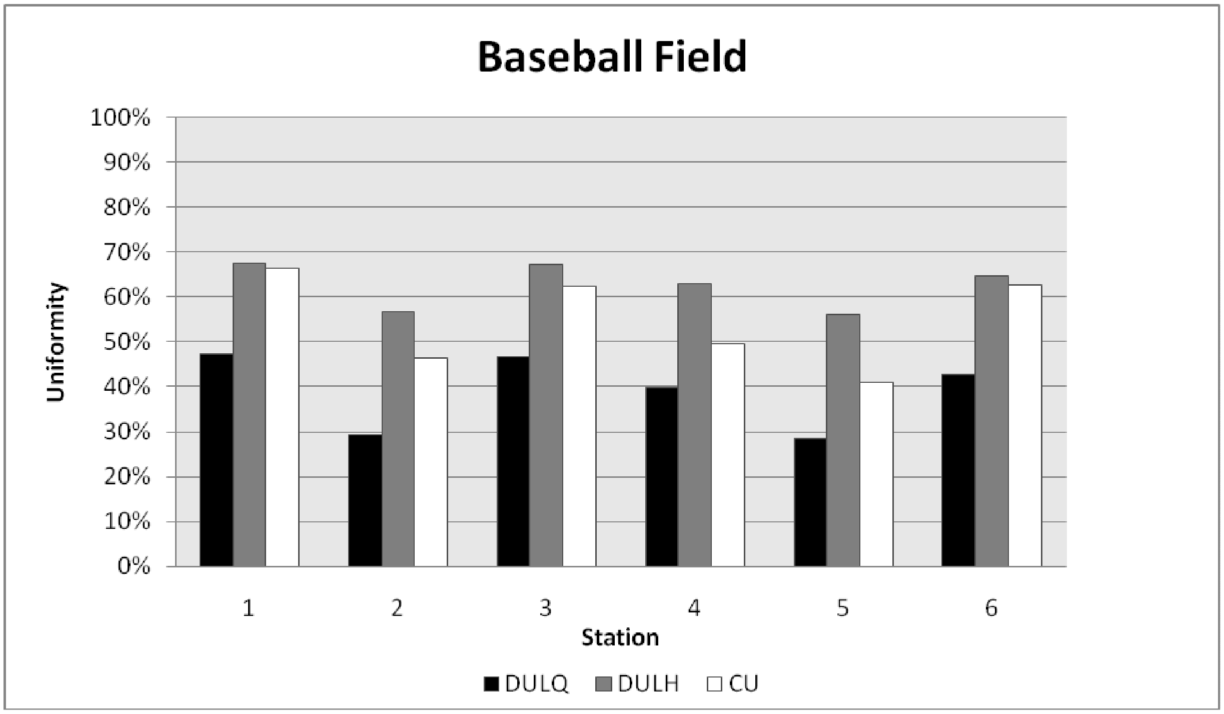

Figure 3. Comparison of Uniformity Values for a Baseball Field

Summary and Conclusion

The DU_{LQ} method, on average, produced the lowest measure of uniformity per station. The DU_{LH} Method produced uniformity values that, on average were higher than the CU method. Overall, the analysis showed that for the same station, the CU method produced on average higher uniformity values than DULQ. These results indicate that similarities exist between the DU_{LH} and the CU methods, but further statistical analysis is needed to show which method produces the more representative uniformity value.

Acknowledgements

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Effect of Sub-surface Drip Irrigation and Shade on Soil Moisture Uniformity in Residential Turf

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Abstract

Sub-surface irrigation in turf has advantages over traditional sprinkler systems. Evapotranspiration is reduced and water applied below the root zone promotes deeper root growth. Auditing such applications requires measurement of root-zone soil moisture. Data was taken on a private lawn that had just been rebuilt to include both sub-surface drip and overhead spray irrigation systems. A portable wave reflectometer was used to take geo-referenced soil moisture readings in the top 5 inches of the root zone before and after scheduled irrigation events. Readings were taken in at 3 - 4 foot intervals. Photosynthetic light and soil moisture were logged at 1-hour intervals in sunny and shady areas of the property. Soil moisture distribution uniformity was computed. Soil moisture spatial variability was mapped using on-line software. Data showed that in the spring, soil moisture was driven by light. In the summer, root extraction by trees was a more important factor in locating dry areas of the lawn.

Introduction

Residential water consumption occupies a large fraction of many municipal supplies (Baum et al, 2003). For residences with irrigation systems, external water use can be as high as 70% of total consumption (Toro, 2006). Unless carefully monitored, there is a tendency to apply more water than is necessary. This wastes water and energy and can leach valuable nutrients out of the root zone. As water restrictions are becoming ever more prevalent, political, as well as economic forces will be cause for homeowners to increasingly adopt irrigation practices that conserve water.

Evapotranspiration, which represents the amount of water removed from the soil by the atmosphere and roots, is one way in which the timing of irrigation events can be determined. This data can be accessed from local weather networks or calculated from on-site weather stations. It has been shown that irrigation at 100% ET, is not necessary to maintain acceptable turf quality on fairways planted to bentgrass (DaCosta and Huang, 2006), Kentucky bluegrass (Feldhake et al., 1984) and fescue (Feldhake et al., 1984; Fry and Butler, 1989). Deficit irrigation has been shown to promote deeper root depths and increased drought tolerance (Jiang and Huang, 2001). Conversely, excess water, whether from heavy rain or over-irrigation can yield anaerobic soil conditions and a moist environment that is conducive to the spread of fungal pathogens. Incidents of over-irrigation are more likely to occur late in the season, assuming irrigation schedules have not been adjusted to reflect shallow root systems resulting from summer heat stress. Lacking the root depth typical of early season, the turf can no longer access the same depth of soil-held water. Consequently, turf water consumption decreases without a corresponding decrease in applied water.

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Although in some areas, such as the arid southwestern region of the U.S., there is a trend to taking landscaped areas out of turf, a lawn comprised of grass is still a highly desirable feature for many homeowners. Apart from aesthetic appeal, there are several ancillary benefits of turf. Turf provides a cooling effect for the property which can reduce air conditioning costs. It absorbs millions of tons of dust and dirt each year. Lawns also act as a filter that can capture and break down pollutants before they reach the ground water supply (Toro, 2006).

Irrigation systems for turf are almost universally comprised of overhead sprayers or sprinklers. Overhead irrigation components are straightforward to install and it is relatively easy for a homeowner to make a qualitative assessment of performance. However, the effects of wind, sprinkler overlap, and evapotranspiration can lead to application disuniformities which, in turn, can lead to excess water application. Drip irrigation has been used in horticultural operations since the middle of the 20th century (Hillel, 2008). There have been some investigations of the viability of using sub-surface drip irrigation (SSD) to irrigate turf grass (Zoldoske, 1995; Leinauer and Makk, 2005; Johnson and Leinauer, 2004; Devitt and Miller, 1988; Ferguson, 1994) Some of the benefits of SSD over conventional irrigation are that it operates at lower volumes and flow rates, puts water directly into the root zone, and is thus less susceptible to losses from wind and evapotranspiration. Leinauer and Makk (2005) found SSD had a higher incidence of localized dry spots than sprinkler or sub-irrigated tile systems. Johnson and Leinauer (2004) studied SSD with saline water in warm and cool season grasses. When using similar water quality, sprinkler and SSD had similar rates of establishment. With saline water, SSD was comparable to sprinkler irrigation for warm season grass. Devitt and Miller (1988) studied SSD with saline water in clay and sandy loam soil. Plant response was limited by salinity in the sandy loam soil. The clay soil was more affected by available soil moisture. Drip line spacing must be adapted to the soil texture to avoid striping (Ferguson, 1994) and must be combined with proper leaching fractions to achieve ideal soil moisture uniformity and minimize salt buildup (Devitt and Miller, 1988).

With conventional irrigation systems, one technique for evaluating performance is to perform an irrigation audit. The Irrigation Association has published guidelines for performing irrigation audits (IA, 2007). Catch cans capture the water applied during a typical irrigation cycle. Distribution uniformity is calculated as the ratio of the average from the 25% of cans that collected the smallest amount of water to the average across all cans (Kieffer and O'Connor, 2007). A similar parameter, Emission Uniformity (EU) can be calculated for drip systems (Schwankl and Smith, 2009). A typical data set would be the amount of water discharge after 30 seconds from each of 36 emitters located between the head and end of laterals across the entire irrigated area. The EU can then be calculated as:

$$EU\% = 100 * \frac{\overline{D}_{lq}}{\overline{D}_{total}}$$

Where:

$\overline{D}_{lq}$ = Average 30-second discharge of the lowest 25% emitters.

$\overline{D}_{total}$ = Average 30-second discharge of all emitters.

A design EU of 90% is considered excellent while an EU less than 70% is considered poor (Peacock, 1998; Lamm et al, 2001). Unfortunately, for an installed SSD system, it is not possible to collect emitter discharge data.

In recent years, there has been interest in using soil moisture data to compute the uniformity coefficients (Mecham, 2001; Dukes et al, 2006; Vis et al, 2007, Kieffer and O'Connor, 2007). Li et al (2001) found water redistribution to be more important than irrigation uniformity, while Hunsaker and Bucks (1987) determined that soil texture was a more important factor. Miller et al (2005) found no correlation between catch can DU and soil moisture DU. The volumetric water content (VWC) at field capacity, which is soil texture dependent, is a parameter that has been found to have a similar pattern of spatial variability to other stable landscape parameters (Krum et al, 2007). Spatial maps of VWC provide useful information for managing turf grass. Krum et al (2008) used maps of VWC and the normalized difference vegetative index (NDVI) to create site-specific management units for precision agriculture applications. Kieffer and Huck (2008) mapped the spatial distribution on a fairway of catch can data and soil moisture data. Soil moisture distribution was similar at different sampling depths and sampling dates but had no correlation to the distribution measured by catch cans.

Managing turf in shade is not easy. When growing turf in shade, it is important to monitor soil moisture and disease pressure (Rackliffe; Koh and Bell, 2006). Koh et al (2003) studied the effect of light and airflow on golf course greens. They found no difference in soil moisture content between treatments.

This paper looks at how soil moisture variability in a lawn irrigated with sub-surface drip is influenced by light and tree root activity.

Materials and Methods

Data were collected in 2008 and 2009 on the lawn of a private residence in northern California. This lawn was subject to a major renovation in 2008, during which approximately 12 inches (approximately 320 yards) of poor-quality, clay soil was removed and replaced with a sandy loam soil. A sub-surface drip system (Netafim-USA Inc., Fresno, CA) and a surface spray system (Hunter Industries, San Marcos, CA) were installed. The drip system is the main irrigation apparatus. The surface irrigation was used to aid with establishment of the sod as well as to perform periodic flushing of the root zone. The drip system consists of 8 irrigation zones (figure 1) which take into account the microclimate (sun and wind exposure), root intrusion from existing large trees (Redwood, Oak, and Willow), and topography. Zones A and H are in full shade. Zone A is relatively flat while zone H is steep and slopes toward the patio. Zones G and F are partial or filtered sun. Zones B, C, D and E are in full sun. Zone C is relatively flat except near the boundary with B. Zone B has a sharp change in grade of 6 inches in 2 feet. Zone E is fairly steep and flattens out as it progresses into zone D. The main irrigation line runs horizontally across the lawn, passing through zones A, C, and F. The soil around the main line was not compacted as heavily as other parts of the lawn when the new soil was added.

Figure 1. Outline of Irrigation Zones

All lateral drip lines were set at 12-inch spacing with emitter spacing of 12 inches (figure 2). The smallest zone is 300 sq. ft. and operates at 3 gallons per minute (GPM) using 1 inch of fill. The largest zone is 2800 sq. ft and operates at 28 gallons per minute (GPM) using 1½ inch of fill. Before laying the sod, the soil surface was inoculated with mycorrhizal fungi to aid root development and plant health. 12,000 sq. ft. of sod (Dwarf Fescue) was installed and ready for mowing in three weeks.

Figure 2. Adding soil over sub-surface system in Zone A

During the summer of 2009, volumetric water content and photosynthetically active radiation (PAR) were measured at a shaded and full-sun location with two WatchDog mini-stations (Spectrum Technologies, Plainfield, IL). The full-sun station was located in zone B, the full-shade station was located in zone H.

The spatial variability of soil moisture was measured using a TDR300 portable wave reflectometer (Spectrum Technologies, Plainfield, IL). Sampling was done to a depth of 4.8 inches. Readings were taken at 4 ft intervals along the boundary of the property. The interior of the property was grid-sampled at the same interval. Data was geo-referenced with a GPS 72 GPS receiver (Garmin International, Olathe, KS). The property had been sampled before the renovation. Soil moisture readings were taken regularly from just after the sod was first mowed (September, 2008) until October, 2009. 2-dimensional contour plots of each data set were generated using the SpecMaps

Web Mapping Utility (Spectrum Technologies, Plainfield, IL). Lower quartile distribution uniformity (DU_{lq}) was calculated for each data set. DU_{lq} is the ratio of the average the 25% of the driest data points to the average the entire dataset.

$$DU_{lq} = 100* \frac{\overline{VWC}_{lq}}{\overline{VWC}_{total}}$$

Where:
$\overline{VWC}_{lq}$ = Average the lowest 25% of readings in the data set.
$\overline{VWC}_{total}$ = Average of all VWC readings.

Results and Discussion

The site of this study is a private residence in northern California. It has been managed by Water Scout Inc. for 12 years. The property is relatively flat in the center and western sections. But, the northern and eastern portions slope, sometimes steeply, toward the northern patio area. The combined effect of topography, light and wind levels, and drastically different soil textures made maintaining aesthetic uniformity an ongoing challenge. Figure 3 shows light levels from areas of the property in full sun (center) and partial shade (outer perimeter). In July, maximum photosynthetically active radiation (PAR) was about 2100 µmoles/m^2/s in the full-sun areas and 1500 µmoles/m^2/s in the shaded areas. The accumulated daily light integral (DLI) for July varied between 1507 moles/m^2 in sun to 677 moles/m^2 in the shade. By September, the maximum PAR values were down to 1600 µmoles/m^2/s in sun and 750 µmoles/m^2/s in the shade. Monthly DLI was 1128 moles/m^2 in sun and 346 moles/m^2 in shade.

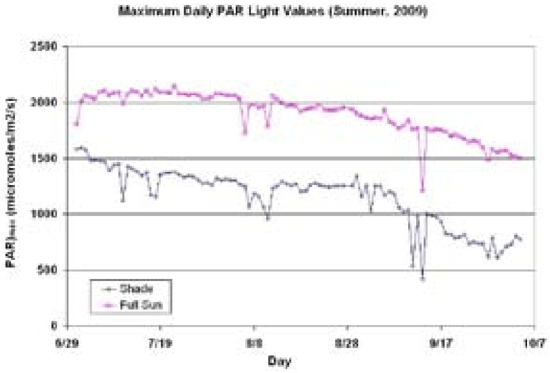


Figure 3. Maximum photosynthetically active radiation (PAR) levels in shaded and sunny zones of property.

Because there was an amalgam of different soils, there were areas that would become waterlogged while others would remain excessively dry. In 2008, the homeowner ordered a major renovation of the lawn. Figure 4 shows a map of the variability of the soil moisture across the property before the renovation. The distribution uniformity of the soil moisture on this sampling date was 57% which was typical for this site. There was a wide gap between the wettest and driest areas of the lawn which is partially a function of the multiple soil types present. On this date, the soil moisture gradient roughly follows the topography of the site.

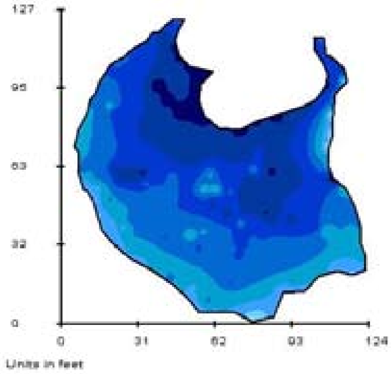


Figure 4. Map of soil moisture variability before renovation (DU=57%)

Figure 5 shows data taken during the period just after the sod was laid in the summer of 2008. The soil needed to be kept very wet during this time to ensure the sod properly knitted. During this period, approximately 60% of the irrigation was from overhead spray and 40% was supplied by the sub-surface drip system (SSD). At this time, environmental impacts on the lawn are not yet visible in the image of soil moisture variability. Data from several sampling sessions during this period yielded DU's of about 85%. Because the irrigation frequency was high at this point, this can be considered near optimum for the newly built lawn.

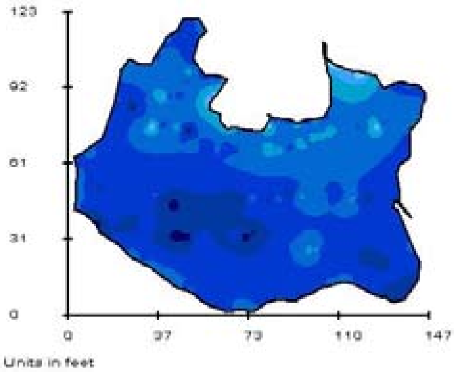
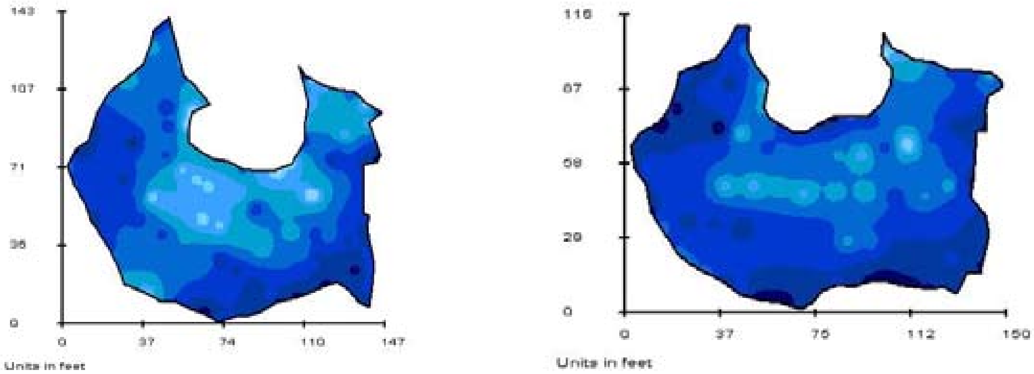


Figure 5. Soil moisture variability map just After laying of sod in summer of 2008 (DU=85%).

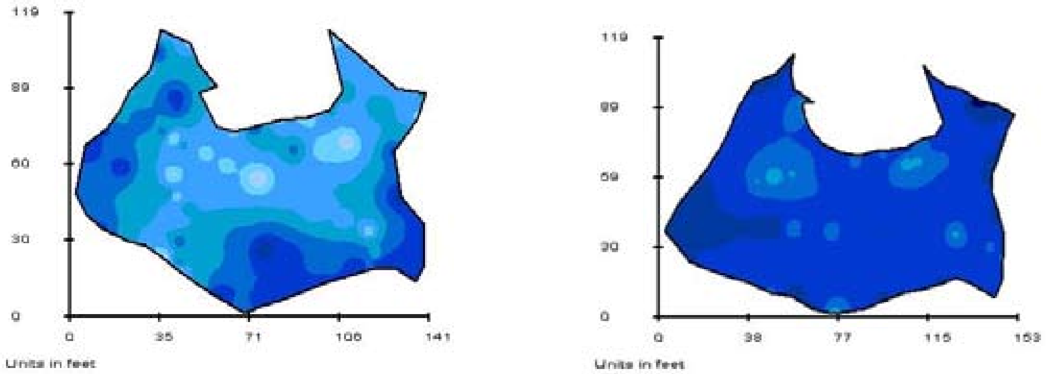
Figure 6 shows the results of data sets taken before and after an irrigation cycle. At this point overhead and SSD irrigation are still being employed. The pre-irrigation data show a DU of 80%. In figure 6b, the data set taken one hour following a full irrigation cycle, the soil moisture pattern is visibly less variable and the DU increased to 87%. The soil moisture movement in this strip of the lawn is currently displaying differences from the adjacent parts of that zone. Inspection of the pre-irrigation map (figure 6a), shows that the soil moisture variability is aligned roughly along the lines of the irrigation zones. The drier (light blue) areas are located in zones B, C, and E while the wetter parts of the lawn are in A, F, and H. Zone G is also seen to be drier. This is attributed to a magnolia tree located in the very middle of that zone. In figure 6b it is possible to see the location of the buried main line which, in this case, is drier than the surrounding soil.



a. **b.**

Figure 6. Soil moisture variability maps from early spring, 2009. a.) data taken prior to irrigation (DU=80%), b.) data taken after irrigation (DU=87%)

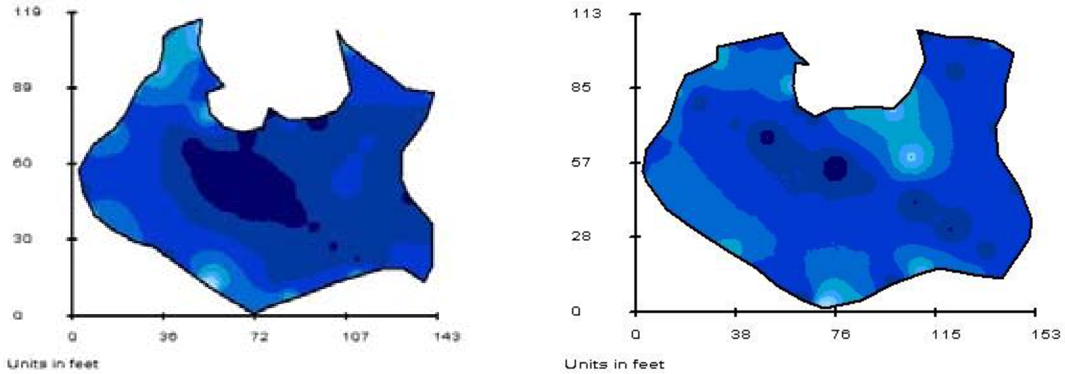
In figure 7 are examples of maps of the property with dramatically different soil moisture levels. These maps were created in the spring of 2009. Both maps are using the same color legend. The map in figure 7a was taken just after it was discovered that there was an electrical failure in the control system that left the lawn un-irrigated for 2 days. It is very clear that the lawn is much drier than in figure 7b which was created later in the season when the lawn received ample water. The DU for the dry sampling date was 73%. The DU for the well-watered lawn was 89%. The maps can, again, be seen to align with the irrigation zones. The driest areas are in the middle and the wetter areas are on the periphery.



a. **b.**

Figure 7. Soil moisture variability maps from late spring, 2009, a.) data taken prior to irrigation (DU=73%), b.) data taken after irrigation (DU=89%).

Starting in July, there was a transition in the soil moisture variability maps. Figure 8 shows data from July and August. The DU for both data sets is about 81%. However, the dry areas have shifted from the zones in full sun to the shaded areas on the periphery. It appears that the roots from the trees are now the dominant influence for extracting water from the lawn. The portion of the lawn above the main line is very visible in these images. However, at this point, it is the wetter part of the lawn. Also visible in figure 8b is a very dry spot in zone E. This is due to two failures in the system. First, a short in the controller wire that left that area un-watered by the drip system. At the same time, there were hardware problems with the overhead sprayers. This left that zone extremely dry and required immediate attention.



a. **b.**

Figure 8. Soil moisture variability maps from autumn, 2009, a.) data taken prior to irrigation (DU=81%), b.) data taken after irrigation (DU=80%).

Figure 9 shows a map of a data set from the autumn. The light level is less and the pattern of variability of soil moisture continues to be driven more by tree root activity than by ambient light. This data set was taken just before a full irrigation from the drip system and the DU is about 78%.

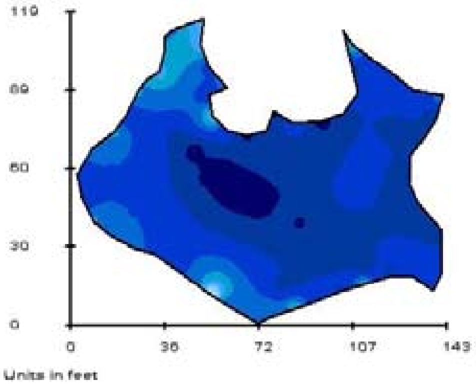


Figure 9. Soil moisture variability maps from autumn, 2009 (DU=78%).

Conclusions

A portable wave reflectometer was successfully used to track the effects on the spatial variability of soil moisture on a constructed turf landscape. The site is primarily irrigated with subsurface drip irrigation (SSD) but an overhead spray irrigation system is also installed and can be used for leaching applications or when the SSD system malfunctions. Tracking soil moisture is critical for managing irrigation because traditional irrigation audit techniques using catch cans cannot be used for subsurface applications. Irrigation zones on this site were delineated mainly by light level and topography. In the spring, soil moisture variability appears to be influenced by the amount of light in each irrigation zone. However, beginning in July, there is a transition. At this point, water extraction by tree root zones better describes the pattern of soil moisture variability. Distribution uniformity of soil moisture was greatly improved on this property after the SSD system was installed. DU went from 57% before reconstruction to DU's of around 80% after. Comparison of data sets taken before and after irrigation found that DU was slightly higher following irrigation events.

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Ragle Park Water Conservation Program

Presented by Peg Aguilar
Sites Southwest

Abstract:

This 22 acre sports park renovation project will replace the existing inefficient irrigation system and provide additional recreation amenities such as a new playground and a splash play area. Sensitive to public perceptions regarding waste water, the designers decided to harvest all runoff from the splash play area, and re-use the water for irrigation to the baseball fields as well as water for the rest room toilets. The presentation will demonstrate the challenges faced in utilizing a cistern system for irrigation with both harvested grey water and potable water. The session will show how harvested water and irrigation water needs within the park are calculated. It will also show how the system was introduced to the public as an interpretive educational element within the park.

Keywords:

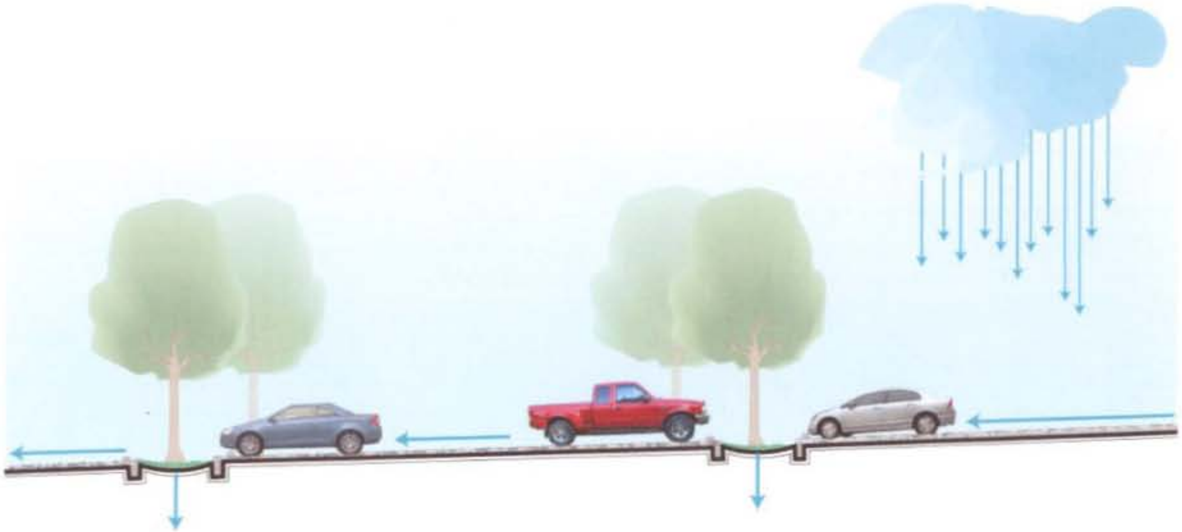
Cistern, pump, water harvesting, non potable irrigation

Water conservation is of great importance in Santa Fe, New Mexico. This 22 acre sports park renovation project will replace the existing inefficient irrigation system and provide additional recreational amenities such as a new playground and a splash play area.

The City of Santa Fe is located in a pinon-juniper environment at about 6600 feet in elevation. Annually, the City receives about 14" in rainfall and another 17" in snowfall. Residents in Santa Fe have reduced their personal water consumption by 31% over the last ten years. In 2007, the documented per capita water consumption was 101 gallons.

Ragle Park is managed by the City of Santa Fe under the Parks and Recreation Department. The Department often receives phone calls from local residents commenting or inquiring about the City's water management practices. So public perception of a water feature within the park was important to consider.

The existing irrigation system is over 30 years old. The park renovation is projected to cost approximately $1.8 million dollars. The proposed park site will have 2 acres of warm season native grass and 8 acres of cool season turf grass, of which 3.35 acres are dedicated to the baseball fields. The remaining park is dedicated to parking, a rest room and concessions building, a large playground, a batting cage and the splash pad. The irrigation system is to be completely replaced, including the controller, backflow preventers and all valves, heads, piping and a new cistern system and pump. Several areas of the park will be passively harvesting drainage from the parking lots into retention areas and depressed parking islands.



Early in the design process, a re-circulating type of system to capture, treat and re-use water within the splash pad system was ruled out as an option due to the high cost of the system and daily maintenance requirements. Overall, the splash pad system consists of a constant pressure mainline, which leads to a valve manifold of bronze solenoid control valves, a pressure gauge and pressure regulator. The system is user-operated by means of a wireless bollard activator. The splash pad for the park will contain seven components, with gentle surface sprays for younger children and larger overhead sprays including a Sea Dragon for older children. The components were selected based on the variety of spray patterns and because they featured Water Conservation options which reduced the demand of the system. The components range in demand from 4 to 14 gallons per minute each. The total potential water use of the splash play area at 100% use is 49 gallons per minute. The system will be pre-programmed to provide greater control over water consumption. At capacities ranging from 80% to 100% of the peak use, the drainage from the splash pad for a typical 8 hour day is estimated to be 19,700 gallons, minus approximately 15% for what is lost to evaporation and "carry off" (i.e...bathing suits) for an estimated total of water harvested to be 16,700 gallons per day.

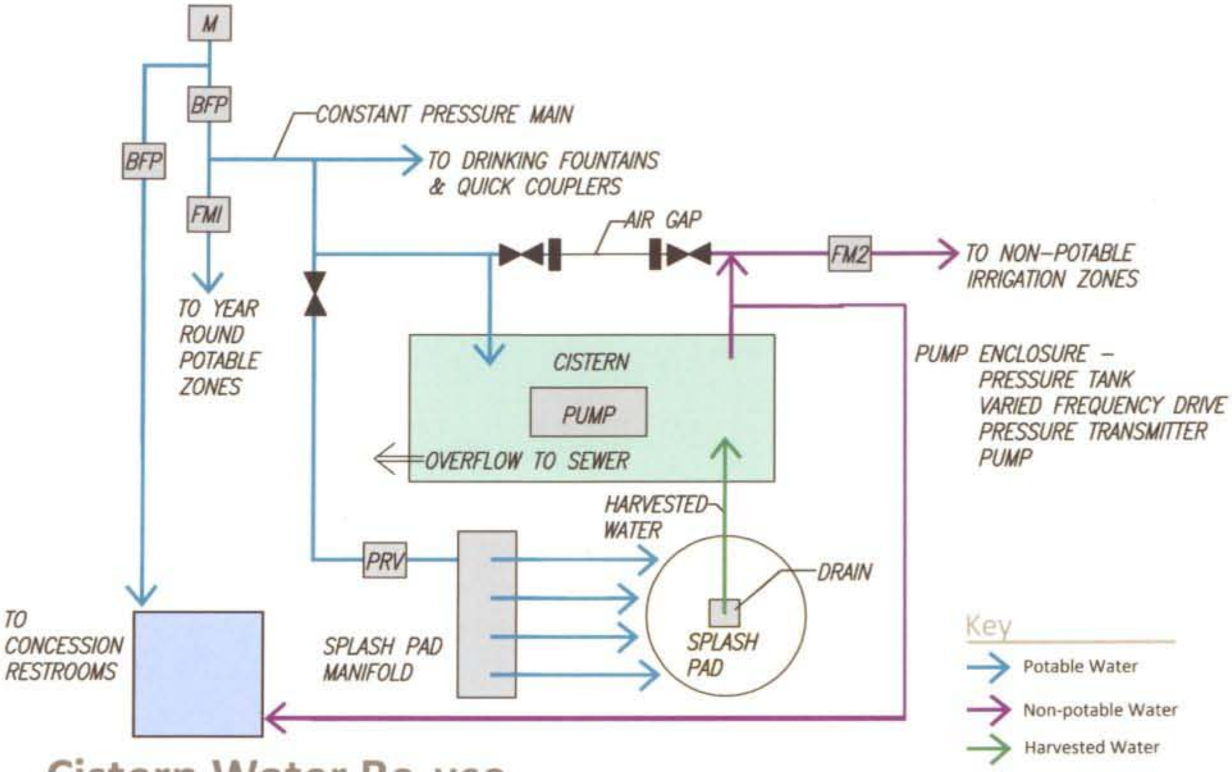
The splash pad itself will drain to a single drop inlet with a basket filter to catch debris. The harvested water will then be stored below grade in a fiberglass cistern. The cistern will be 10 feet in diameter and 64 feet in length, with an overall capacity of 35,000 gallons. This cistern size was based on capturing two 8-hours days of splash pad use. The cistern will have two inlets; one for the harvested water, the other will be a back up water source from the potable water system. From the two outlets, one will supplement the nearby rest rooms for flushing of toilets. The second will provide non-potable irrigation water to the turf grass baseball fields. A third overflow outlet will be provided which will tie into the sewer system at the concession building, in case of any overflow.

The cistern system will be operated by the irrigation controller. When a control valve is activated, the system will sense a loss of pressure. The pressure transmitter activates the pump, located above the cistern at grade. When the irrigation is off, the system reads the pressure, and the pump is turned off as well. The pressure tank is designed to help adjust to minor fluctuations in water pressure, helping to ensure the pump is not activated when not needed.

The pump is designed as a centrifugal pump with a variable frequency drive for energy savings. The variable frequency drive adjusts the speed of the pump, in response to demand. Originally, the pump system was designed to provide 70 gallons per minute. Once base watering schedules were calculated for all of the zones, the pump size was increased. The new pump will be designed to provide 250 gallons per minute for the irrigation system, allowing for the entire park to be irrigated in one night. This system, while approximately 30% more expensive than the original, provides the high demand needed. The pump system was decided to be above grade to facilitate maintenance. If the cistern pump were submersible, only a certified staff member could enter the cistern to perform maintenance on the pump. For winterization of the system, a sump pump will be used to drain the cistern. The cistern is designed with a low water level sensor, which will communicate to the irrigation controller, opening the master valve if additional potable water is needed.

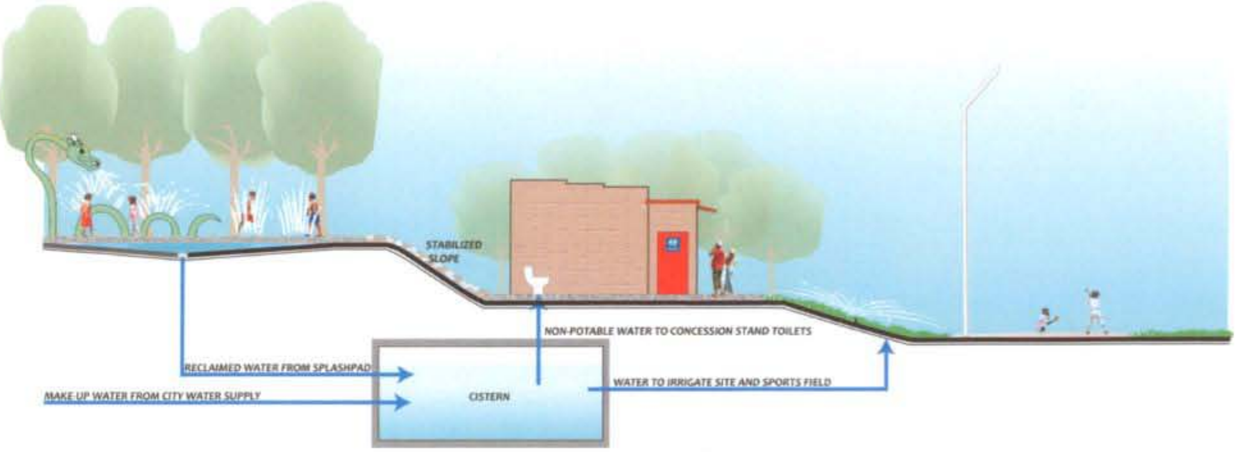
The projected water use for the harvested cistern water was calculated using the Irrigation Association Base Watering Schedule. The schedule was calculated based on a projected 70% distribution uniformity, July historical ET rates, sandy loam soils and three days per week available for irrigation. A base schedule and a run time were calculated for each of the different types of zones. The total peak water use in July was calculated to be 107,300 gallons per complete irrigation cycle for the park. Of this amount, 35,300 gallons, or 33% will be from water harvested from the splash pad.

Since the water harvesting from the splash pad will only be available in the summer months, an alternate system had to be made available to use a completely potable water system during the Spring and Fall. By building in a by-pass within the mainline, the two methods will be easily switched over on a seasonal basis. The diagram below describes the overall irrigation system.



Cistern Water Re-use

In order to inform and educate the public, a series of interpretive signs like the one shown below will be posted in the park describing how the water is captured and where in the park the water is being re-used. Each of the baseball fields that utilize the harvested water will have signage as well.



Conclusion:

Water harvesting from a water feature allows local parks departments to provide a valuable summertime amenity, while conserving potable water. Affective communications, through educational signage can help the public to understand the value of resource conservation efforts. By irrigating with the harvested water, approximately 1.28 million gallons of potable water is projected to be saved in the peak water use month of July. Future data collection by the Parks Department will tell them not only the annual reduction of potable water use, but the annual savings, as compared to the cost of the system.

sites
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Irrigation
ASSOCIATION

Evaluation of Irrigation Smart Controller for Salinity Control

Ram Dhan Khalsa[1] PE, CAIS, CIC, CID, CGIA, CLIA, CWCM-L

Abstract

The purpose of this paper is to summarize the results of an investigation to determine whether Smart residential irrigation controllers with customized site specific programming, are an effective means of reducing irrigation water usage and the associated deep percolation in arid, salinity-rich soils. A joint effort between the Department of Agriculture (on-farm program) and Department of Interior (off-farm program) in reduce salt loading to the Colorado River has been underway for 25 years. Deep percolation has been quantified for agricultural land converted to residential sites in a previous two-year study. Four residential sites were monitored for a third year to evaluate the performance of Smart irrigation controller irrigating schedules. The results of the investigation provide Bureau of Reclamation and the Grand Valley community with information to support the implementation of best irrigation management practices to reduce ground water salinity loading.

Introduction

Deep percolation of irrigation water has been quantified for agricultural land use in a monitoring and evaluation study by the Natural Resources Conservation Service (NRCS) (U.S. Department of Agriculture, 1986-2003). The U.S. Geological Survey (USGS), in cooperation with the Colorado River Salinity Control Forum and the Mesa Conservation District, quantified the current (2005-2006) deep percolation characteristics of agricultural land that was converted to residential lots and estates, urban parks, and pasture grass fields in the Grand Valley. The two-year study for the years 2005-2006 found that both irrigation water use and deep percolation were lower for he residential lots and estates when compared with traditional surface irrigated fields in the NRCS study.

Purpose and Scope

The purpose of this report is to summarize the results of an investigation to determine whether Smart residential irrigation controllers, which use on-site weather data and customized site specific programming, are an effective means of reducing deep percolation and irrigation-water usage. This report contains the results of a year of data collection for 2007 that used Smart irrigation controllers, with a comparison to the traditional Clock type controllers that were used it the previous two-year study of residential sites in and near Grand Junction, Colorado.

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There are many models of Smart controllers on the market. In this study the Smartline SL 1600 irrigation controller with weather monitor was selected to represent Smart controllers.

The Smart controller determines the daily irrigation-water requirement by calculating a water-deficit using site-specific parameters. The study quantified amounts of irrigation-water use and deep percolation from the use of Smart controllers. The human factors associated with a change to this new type of controller were also evaluated, such as homeowner acceptance of the technology, the homeowner's perceived quality of the lawns during the study, and the success of the homeowners in utilizing the more complex features of the controller. The two-year study quantified irrigation water application and deep percolation for the traditional Clock type controller at each site. The goal of this study is to do the same with the Smart controller. Ideally, a direct comparison of the two types of irrigation controllers might be possible. The results of the investigation provide Reclamation, USGS, and the Grand Valley community with information needed to support the use of Smart controllers for salinity control.

Description of Study Area

The study area is located in the Grand Valley of Mesa County in Western Colorado, near the confluence of the Gunnison and Colorado Rivers (fig. 1). The valley is approximately 30 miles long and 5 miles wide. Geologically, the Grand Valley is underlain by Mancos Shale, which is a non-point source for salt and trace elements such as selenium (Butler and others, 1996). Deep percolations of irrigation waters in the Grand Valley can leach considerable salt and selenium from Mancos Shale-derived soils.

Site Selection and Characteristics

There were four monitoring sites, consisting of two ¼-acre residential lots and two 5-acre estates in the Grand Valley. A summary of site characteristics is listed in table 1. Site numbers are retained from the two-year study. The 2 residential lots were located in two subdivisions (Chipeta Pines and Paradise Hills), one on the north side of the Colorado River, and one on the south side. The estates were both located in the Quail Run subdivision on the north side of the river.

Kentucky bluegrass was the turf studied on the four sites. These residential sites used underground pop-up sprinkler systems. Sprinklers include both impulse and spray types. All sites used irrigation ditch water rather than treated potable water.

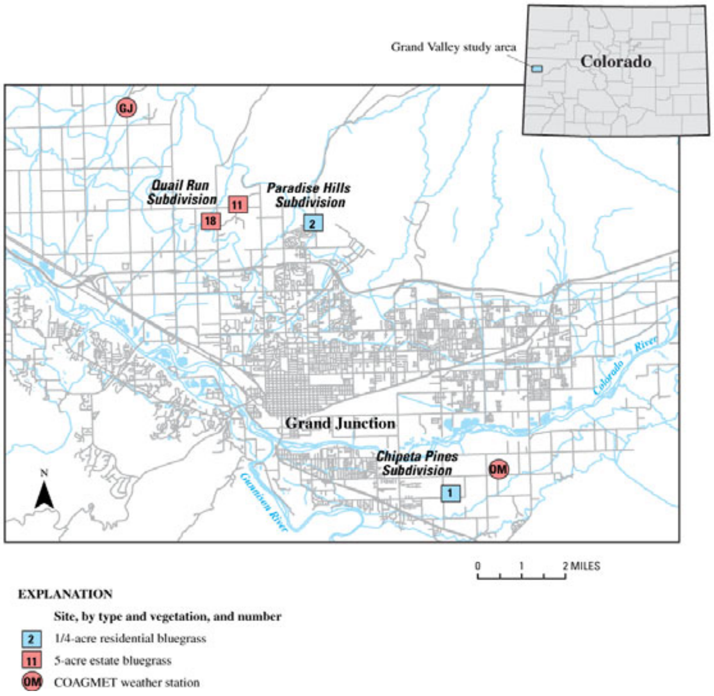

Figure 1: Residential Smart irrigation-controller study site locations in the Grand Junction, Colorado

Table 1. Characteristics of urban study residential ¼-acre lots and 5-acre estates
[Site number, refers to sites published in initial two-year study (Mayo, 2008)]

Site number	Years Studied	Subdivision	Site type	Irrigated turf acreage	Vegetation	Number of irrigation zones	Average gallons per minute flow for all zones	Soil type
1	2005, 2006, 2007	Chipeta Pines	¼-acre residential lot	0.12	Bluegrass	10	12	Loam
2	2005, 2007	Paradise Hills	¼-acre residential lot	0.12	Bluegrass	7	22	Clay loam
11	2005, 2006, 2007	Quail Run	5-acre estate	0.14	Bluegrass	3	27	Clay loam
18	2005, 2006, 2007	Quail Run	5-acre estate	0.82	Bluegrass	7	44	Clay loam

Data Collection Methods

The data collection method used is summarized in table 2. Data collection at the sites included two digital data loggers: (1) to record irrigation- events at the irrigation controller, and (2) to record irrigation-system water pressure. The irrigation events were logged for each sprinkler zone, with a data logger (fig. 3). The water pressure logger recorded the pressure in the irrigation mainline (fig. 4). This provided different information, depending on the type of site water pressure was an indication that the system was actually delivering water, and again served as a cross-check of the sprinkler-controller events.

Table 2. Data collection methods
[CSU, Colorado State University; CoAgMet, Colorado Agricultural Meteorological Network; USGS, U.S. Geological Survey]

Data collection method	Collection frequency	Data source
Irrigation-event log	Every minute	Irrigation-event logger wired to each zone valve at the irrigation controller
Water-pressure log	Every 2 minutes	Data logger with pressure sensor on irrigation system mainline
Flow rate per zone	Twice during two-year study	Field measurement by USGS using acoustic flow-meter
Effective precipitation	Every 60 minutes	Two CSU CoAgMet Weather Monitors, adjusted for runoff
Evapotranspiration	Daily calculation from climate data	Two CSU CoAgMet Weather Monitors
Gravimetric Soil moisture	Monthly	Collection by USGS of 12-inch soil core sample
Irrigation Audit	Each site during the two-year study	CSU Cooperative Extension measurement of distribution uniformity using catch can method

Smart Irrigation Controllers

The existing Clock controllers were removed from all four sites, and Smart irrigation controllers were installed (fig. 2). The Smart controller operates in either of two modes: (1) standard; and (2) auto-adjust. In standard mode, no water deficit calculations are made to adjust the zone run-times of the program. The standard-mode station run-time settings are used to identify the stations used for automatic irrigation. The manual sprinkler run-times are used as default values in auto-adjust mode if communication is lost with the Weather Monitor. In auto-adjust mode, the settings for standard-mode watering days and start time are still used, but the zone run-times are automatically adjusted by the controller. In auto-adjust mode, the controller calculates the water-deficit (ET) for the day just concluded, and sums each day's ET since the last irrigation.

Figure 2: Smart irrigation controller.

Site Visits

Each site was visited at least once a month from June through October, 2007. Data loggers were checked and downloaded, homeowner questions were answered. Soil-moisture core-samples were collected for gravimetric soil-moisture calculation as a cross check against calculated soil-moisture balance.

Figure 3: 22-channel digital irrigation event data logger.

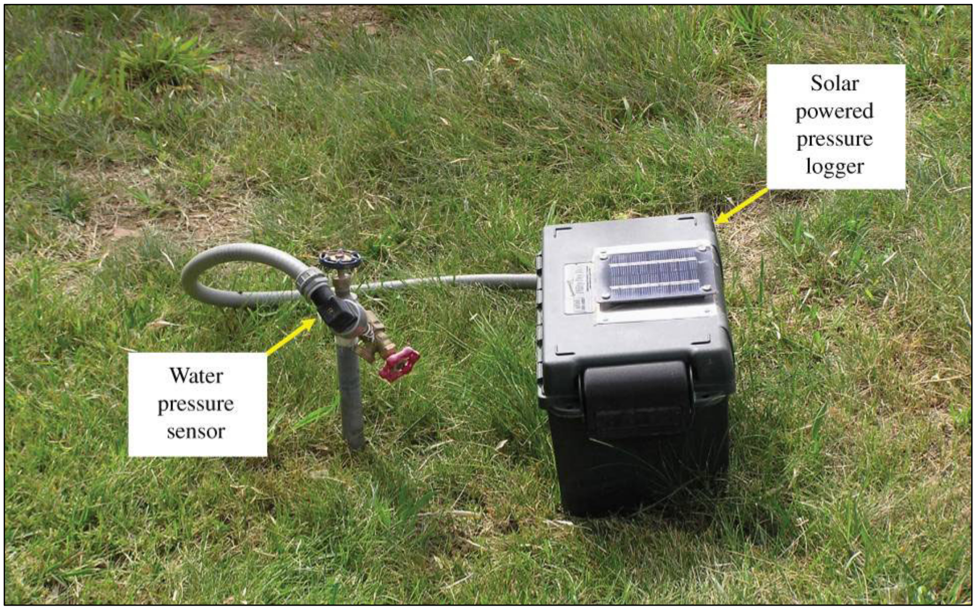

Figure 4: Solar powered digital water pressure logger.

Zone Flow Rate

By knowing the average water flow-rate per zone, a calculation of the total quantity of water delivered during an irrigation event can be made by multiplying the zone flow rate by the zone irrigation duration. Zone flow rates were measured using an acoustic flow meter at each sites. Water pressure was simultaneously recorded during the flow test using water-pressure data loggers to determine the variability in supply pressure and to determine an average pressure.

Irrigation Audits

An irrigation audit of each site was performed. This audit measured the distribution uniformity and application rate of the sprinkler system by placing a grid of catch-cans over a section of the lawn (front, back, side, etc), and running each of the zones in that area for a 5 minute interval. The distribution uniformity and application rate were calculated by area, not by zone.

Climate Data

Two CSU CoAgMet Campbell Scientific Weather Station locations (fig. 1), Grand Junction (GJ) and Orchard Mesa (OM), provide hourly climate data for calculating ETr for the irrigation season (Colorado State University, 2005-2007). Effective precipitations from these weather stations were used for the daily soil-moisture balance calculation.

Data Analyses Method

The two quantitative measures of the effectiveness of the Smart controllers used for the study are: (1) the amount of irrigation water applied to the lawn, and (2) the amount of resultant deep percolation. Irrigation water application for an irrigation event is determined by multiplying the run time (minutes) for each irrigation zone by that zone's flow rate (gallons per minute), then totaling for all zones that were active during the event. Zone run time is recorded by the irrigation event logger. Deep percolation for the study is considered to be any water that infiltrates below the top 12 inches of the soil profile. Gaps in the irrigation event log prevented a continuous daily soil-moisture balance calculation at three of the four sites in the study. To compensate for the lack of continuous daily soil-moisture balance values, a calculation of total-season irrigation water application was made, using estimations of the missing irrigation-water application data. Application efficiency is defined for the study as the measure of irrigation water required (turf evapotranspiration – effective rain), divided by the amount of water applied including precipitation.

Total-season and monthly application efficiency were then used to compare the performance of the Clock and Smart controllers.

Daily Soil-Moisture Balance Graph

To visualize the daily irrigation events and soil-moisture balance for a site, a graph was created for each site showing water inputs and outputs, with resulting changes in the soil-moisture balance (for example, see fig. 11a). The vertical axis represents inches of water, with positive values indicating irrigation and precipitation, and negative values indicating deep percolation. The horizontal axis represents days of the irrigation season.

Total-Season Irrigation-Water Application

Monthly and seasonal water application is the sum of the daily values. For days where daily controller log data are missing, it is not possible to calculate a daily water application value. It is possible to estimate a monthly water application total for a site by assuming that the monthly water applied to the lawn is a function of the cumulative reference evapotranspiration (ETr) for the month. This assumption is based on the fact that the Smart controller determines how much irrigation water to apply each day by calculating a daily estimate of evapotranspiration. After subtracting any effective precipitation, the monthly irrigation-water application can thus be estimated using the ratio of evapotranspiration values between two adjacent months (“missing” and “known”).

Total-Season Application Efficiency

Total-season application efficiency is a useful way to compare the performance of irrigation systems from year to year, since it compensates for the quantity of ET in each year. The total-season ET for turf grass can be determined using the total-season alfalfa reference ETr (from CoAgMet) with the standard turf grass crop coefficient Kc (0.66) to calculate ET. A calculation of total-season application efficiency was made by dividing ET by the total water applied including effective precipitation.

The total-season application efficiency may be assumed to be a function of the performance of the irrigation controller. If the Smart controller is making a more accurate determination of the irrigation-water needs of the lawn as compared to the Clock controller, then the seasonal application efficiency should be grater for the Smart controller. By comparing a site’s application efficiency month to month and calculating the coefficient of variation of the monthly application efficiency, a judgment of the relative performance of the two controllers can be made. Common sense suggests that as application efficiency increases, irrigation water use should decrease, and deep percolation should decrease. Grass is relatively tolerant of under-watering and over-watering; one can offset the other in the annual application efficiency. By calculating the coefficient of variation of the monthly application efficiency, a look at the monthly variations can be compared, rather than looking at only the annual application efficiencies. In all sites the Smart controller had a smaller coefficient of variation than with the Clock controller. While not a statistically rigorous analysis, the data from this study indicate a possible correlation between application efficiency, irrigation water application, and deep percolation.

Example: Site 18 Results

The daily soil-moisture balance at site 18 for this study is shown in fig. 11a. For comparison, the two-year study soil-moisture graphs are shown for 2006 (fig. 11b).

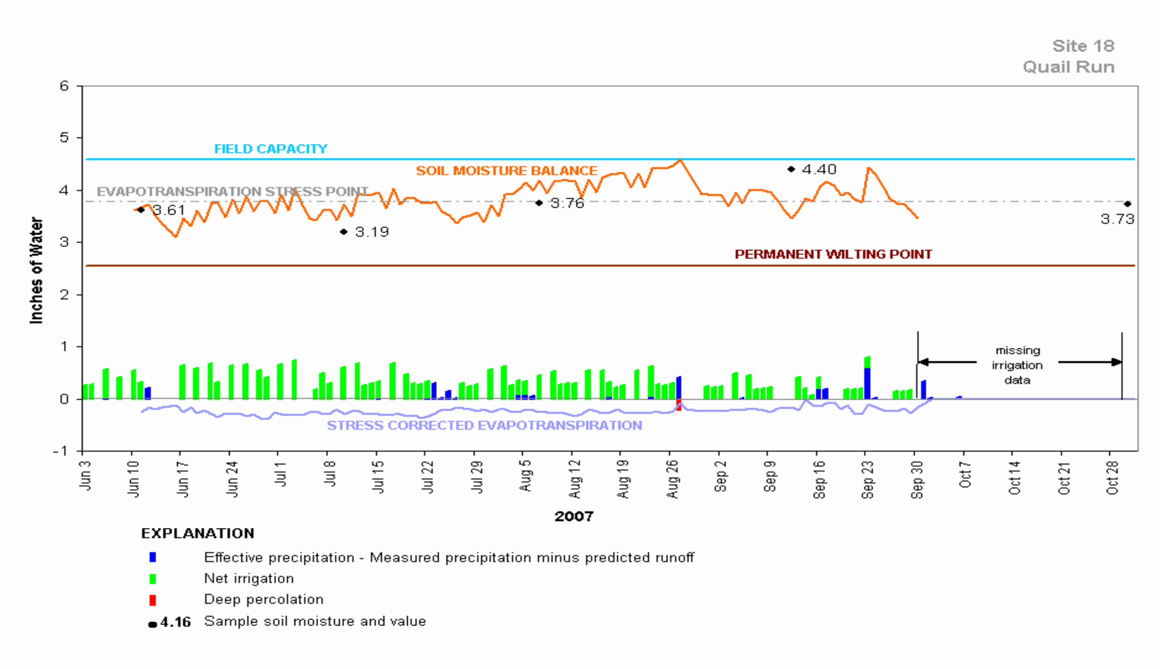

Figure 11a: 2007 Soil-moisture balance for bluegrass for site 18, Grand Valley

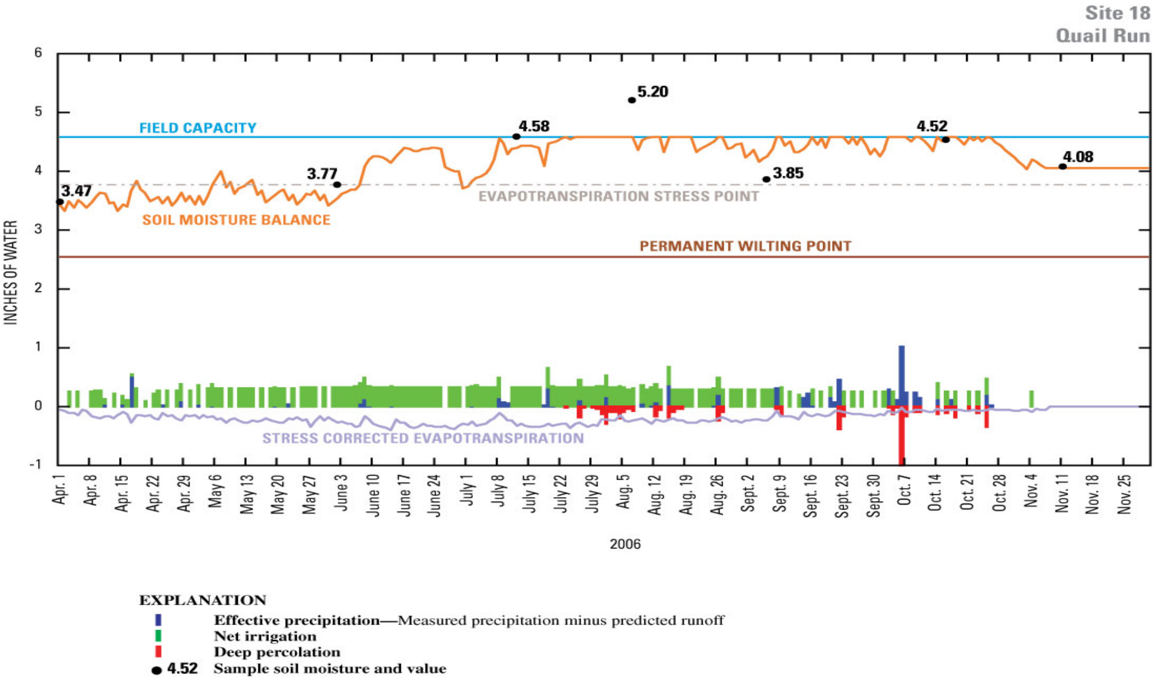

Figure 11b: 2006 Soil-moisture balance for bluegrass for site 18, Grand Valley

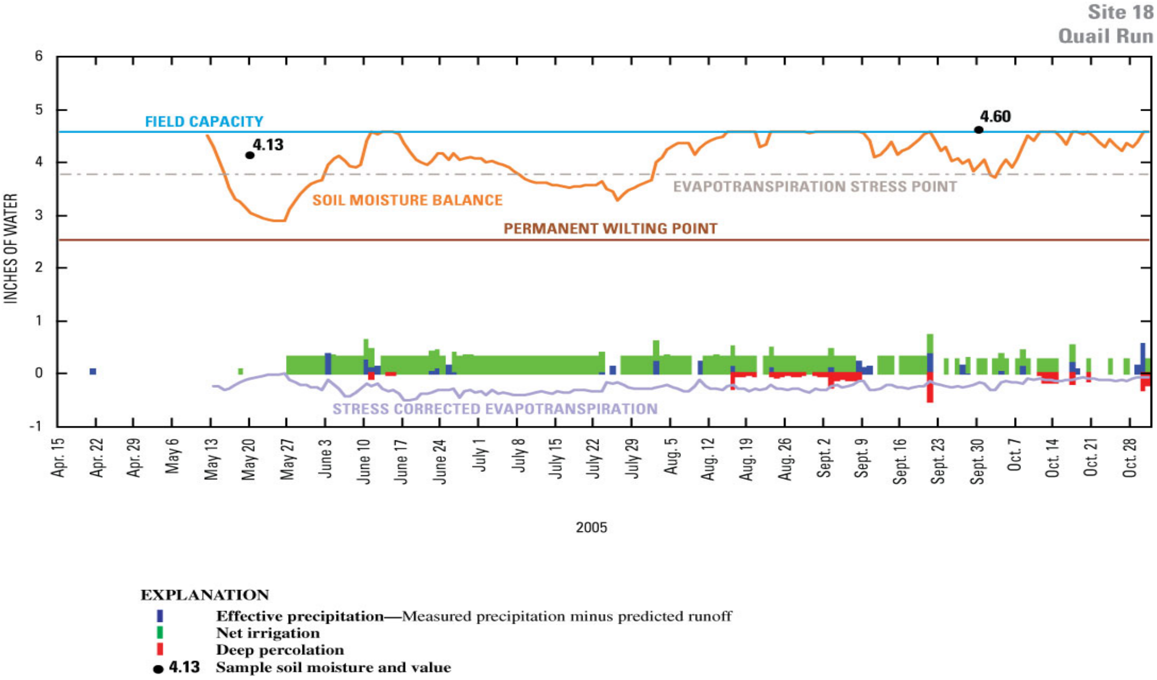

Figure 11c: 2005 Soil-moisture balance for bluegrass on 5-acre estate site 18

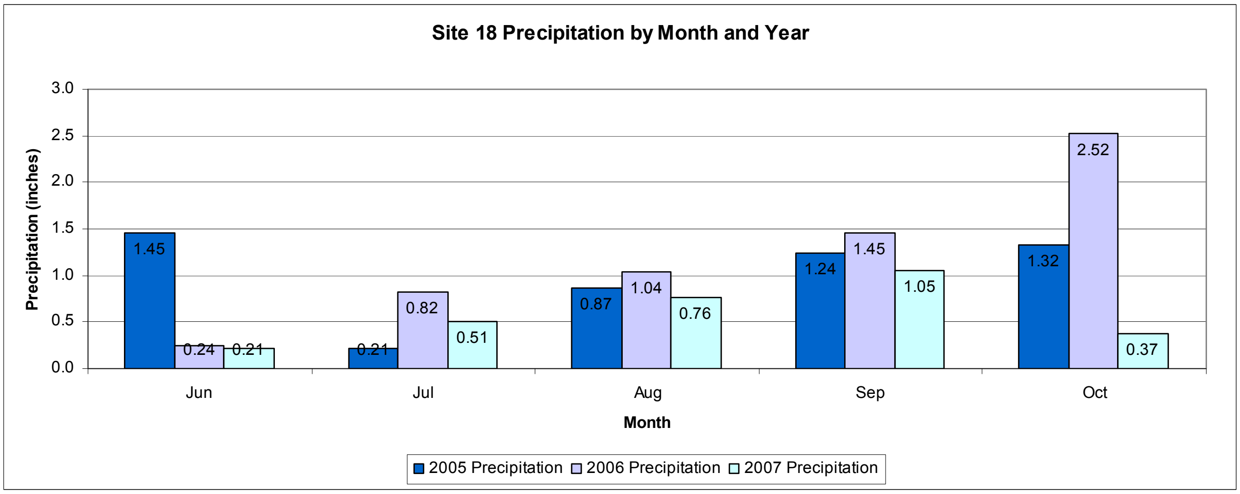

Figure 12a: Three-Year comparison of monthly effective precipitation

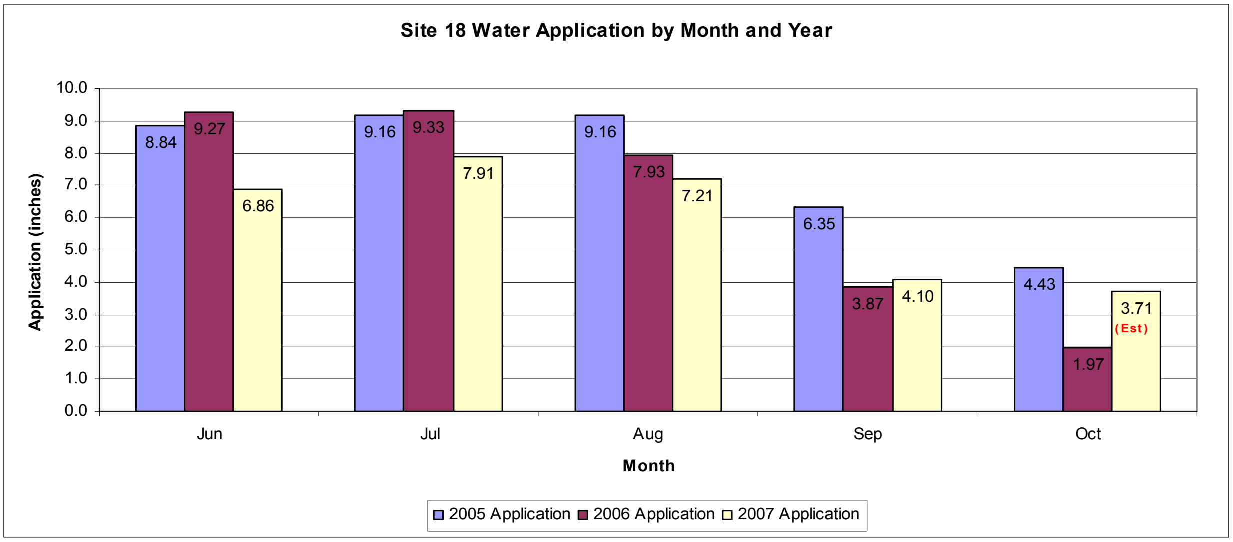

Figure 12b: Three-Year comparison of monthly irrigation-water application on site 18, (est, estimated value)

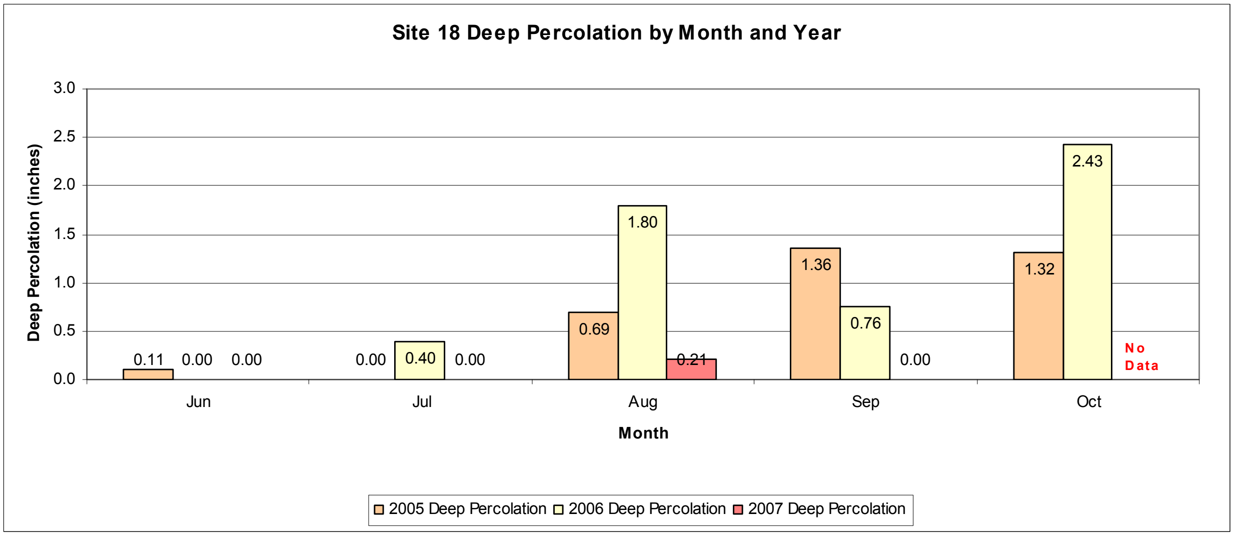

Figure 12c: Three-Year comparison of monthly deep percolation on site 18

Table 11. Monthly precipitation, water applied deep percolation, evapotranspiration, and application efficiency for 2007, 2006, and 2005 on site 18, Grand Valley, Colorado.

Year / Month	Effective Precipitation	Gross Irrigation Water Applied	Deep Percolation	Water Applied + Precipitation	Ref ETr	Crop ETc	Crop ETc - Precipitation	Total Season application efficiency
2007	**2.5**	**26.1**	**0.2**	**28.6**	**35.1**	**23.2**	**20.6**	**72%**
June	0.2	6.9	0.0	7.1	9.7	6.4	6.2	88%
July	0.5	7.9	0.0	8.4	10.1	6.7	6.2	73%
Aug.	0.8	7.2	0.2	8.0	8.4	5.6	4.8	60%
Sept.	1.1	4.1	0.0	5.2	6.8	4.5	3.4	67%
2006	**3.6**	**30.4**	**3.0**	**34.0**	**33.5**	**22.1**	**18.5**	**55%**
June	0.2	9.3	0.0	9.5	10.2	6.8	6.5	69%
July	0.8	9.3	0.4	10.2	9.6	6.3	5.5	54%
Aug.	1.0	7.9	1.8	9.0	8.0	5.3	4.2	47%
Sept.	1.5	3.9	0.8	5.3	5.6	3.7	2.3	43%
2005	**3.8**	**33.5**	**2.2**	**37.3**	**32.4**	**21.4**	**17.6**	**47%**
June	1.5	8.8	0.1	10.3	8.0	5.3	3.8	37%
July	0.2	9.2	0.0	9.4	10.1	6.7	6.5	69%
Aug.	0.9	9.2	0.7	10.0	7.8	5.1	4.3	43%
Sept.	1.2	6.4	1.4	7.6	6.5	4.3	3.1	41%

Post Study Homeowner Interview

Homeowners were interviewed at the end of the study with 15 standard questions to ascertain their experiences and opinions of the Smart controllers. The questions are listed in table 3. All the homeowners were impressed with the automatic operation of the controller. The advantages of the controller were stated as: (1) water was not being wasted; (2) the controller shut off after a rain; and (3) the homeowner did not have to adjust the settings throughout the season. Disadvantages of the controller were mostly stated as the complexity of learning how to use the controller, and not entirely understanding the automatic watering decisions being made by the controller. The reliability of the Smart controller was judged to be good, but several homeowners were concerned about the life of the battery in the Weather Monitor. Smart controller technical support states that the Weather Monitor battery should last 4 years.

Table 3. Homeowner interview questions.
[USGS, United States Geological Survey]

Question Number	Question
1	Overall, how did you like the Smart controller during the study last year?
2	What did you like most about this irrigation controller?
3	What did you like least about this irrigation controller?
4	Did the controller keep your yard adequately watered throughout the irrigation season? How would you rate your lawn?
5	Did you operate the controller in auto adjust, or manual mode?
6	Did you have to call USGS for help with the controller? If so, what did USGS need to do to help you?
7	Have you needed to change the Weather Monitor battery on the roof yet? Do you know how to change the battery?
8	What kind of adjustments, if any, did you make to the controller settings during the irrigation season?
9	Did the controller respond in the way you expected it to?
10	What is your judgment of the quality and reliability of the controller?
11	Do you plan to use the controller next year?
12	Do you think your neighbors would like to use the Smart controller? If so, what would convince them to do so?
13	Do you think the controller saved any water for the season, compared to years past?
14	Why did you decide to keep the controller after the study was over?
15	Are there any other comments or questions that I haven’t asked you?

Conclusion

Based upon the data collected, using Smart controller technology reduced excess deep percolation. Troubles with data collection prevented a more firm conclusion. However, it appears that Smart controllers would help reduce salinity loading in the Grand Valley. The annual application efficiencies results are summarized in table 13.

Table 13. Three-year summary of application efficiency by site number and study year.
[N/A, site not studied that year, data not available]

	Annual application efficiency			
Study Year	Site 1	Site 2	Site 11	Site 18
2007	54%	52%	92%	73%
2006	48%	N/A	54%	55%
2005	54%	43%	69%	47%

Acknowledgements

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Sustainable Landscape Design Strategies for Maximizing Rainwater Use and Increasing Irrigation Efficiency

Landscape is generally considered a decorative commodity in the architectural design field, water industry, and public mind. The American landscape ideal is a water- and maintenance-intensive landscape dominated by lush, green turf that never gets brown, never gets weedy, and in most cases has no relevance to its region, especially in the Southwest. Rooted in the English landscape model of a gentleman's country-estate lawn, the ideal has become a landscape industry convention. Pushing this ideal relentlessly toward prevalence are outmoded design and management mindsets and techniques that create landscapes in conflict with their environments. In the arid Southwest, the consequences of this conflict are nowhere more apparent than in irrigation water use.

The need for intensive irrigation arises when landscapes cannot live and thrive solely through the natural conditions of their environments. This often happens when cultural convention comes into conflict with ecological reality. Instead of self-sufficient, regionally relevant landscapes, we create weak, exotic ornaments that require constant attention. Their irrigation regimes are the equivalent of landscape life support. At the first sign of yellowing grass or brown leaves, we simply increase irrigation. This "just add water" remedy is another convention the landscape maintenance industry, water professionals, and public entities are examining with increasing scrutiny and often rejecting.

Technology alone cannot solve the conflict between water conservation and irrigation-greedy landscapes, though it's where we often go for solutions. Developments in irrigation technology are imperative for addressing water use issues and sometimes provide excellent solutions. However, design and management professionals are increasingly discovering that an integrated, holistic mindset – an approach commonly placed under the banner of "sustainable design" -- can be as or more effective than the best technological tools. When technology is integrated with design and planning techniques, the irrigation efficiency and performance of landscapes move toward a new ideal, one that is regionally relevant, self-sufficient, and regenerative.

Landscaping in the arid zones of the Southwest provides an excellent opportunity for demonstrating the efficacy of sustainable design and management strategies in reducing irrigation demands. With natural rainfall as a pivotal element, my design approach exploits regional environmental conditions instead of disregarding or fighting them, resulting in highly efficient landscapes that generate habitat. Dubbed "total hydrology planning," the approach is an integrated, holistic strategy that includes key techniques often used in sustainable design, though many are also part of conventional landscape planning and management. Like technology, standard practices can play an important role in the irrigation-efficiency solution when integrated in a total hydrology approach. This integrative process dovetails seamlessly with green building, significantly impacting US Green Building Council LEED scores in the credit sections of Sustainable Sites, Water Efficiency, and Energy and Atmosphere, as well as Operations and Maintenance. This paper will discuss how total hydrology planning's essential design techniques – especially maximization of rainwater -- can contribute to landscape irrigation efficiency, and even irrigation elimination.

Strategies

Planning landscapes to capitalize on available rainwater improves irrigation efficiency by manipulating the three components of water catchment systems, water supply, water demand, and how water is delivered to plants. Maximizing rainwater use does more than reduce demand on municipal and other water sources. It improves plant health, lowers maintenance requirements, builds healthy soils, generates habitat, and creates landscapes that are highly relevant to their specific environments.

Total hydrology planning encompasses many strategies that collect rainfall passively, distributing water to plants and retaining moisture through gravity, shade, and topography. These are integrated with active catchment systems, more complex systems that use technology to harvest and store rain, and irrigation technology to achieve efficient goals.

1. Start with a wide, all-encompassing perspective.

Observation with a view toward the big picture is paramount, not just during the data collection phase of design but throughout the process and its evaluation. It starts with a careful examination of overarching factors impacting the site, including those located beyond site boundaries. When planning more than one site, as in the case of a conservation subdivision, boundaries blur even further. Many of the results of this observation step will naturally direct decisions for passive rainwater collection to boost supply and planting selections to reduce demand.

For example, climate data analysis should include average temperature highs and lows, prevailing winds, ambient moisture season to season, and monthly rainfall. Collect site data including property dimensions, municipal location, orientation of buildings, and solar information. Pay attention to adjacent properties and their uses, the topography of the site, and any off-site conditions that can contribute to the water shed. Measure high points, low points, direction of slopes, and unusual circumstances, such as an area that appears to pond or lacks vegetation. Note anything that subtracts or adds to the site's total moisture, such as water draining from a street or parking lot onto the property that can be used to increase to the supply side of the water budget. Inversely, note water that runs onto adjacent property that should be used on-site before it is allowed to drain off. Map out hardscape including parking, walks, and plazas, as well as roof plains of all buildings. Take note of where the water drains from roofs, both drip edge and downspouts, as these will be useful in locating plantings or determining if drainage locations should be adjusted. Learn about vegetation types growing on the site and in the neighborhood. Conduct a visual soil test from multiple locations around the site with a shovel or soil probe, making note of general soil consistency and type, such as clay, sand, silt, and rock. Sometimes, geotech borings from previous construction are available. Take samples from a variety of locations and test for PH and N.P.K. This information will become very valuable.

Observation and analysis of existing conditions were pivotal to the success of landscape at the Northern Arizona University Applied Research and Development Facility, a LEED Platinum project located in the high, dry climate of Flagstaff, Arizona. The site plan was organized around a municipal on-campus basin, a potential constraint we turned into an asset to help meet the project goal of reducing water consumption by 60 percent. We used site-excavated limestone to direct run-off, recycled plant biomass as mulch to build soil, and re-designed the basin as a wetland planted with plant species appropriate to climate and elevation. Combined with active catchment from building and hardscape, the design effectively manages water and fits in with surrounding environment.

2. Calculate supply and demand for a total moisture budget.

Based on site data collected, determine the total moisture budget based on supply and demand. When calculating supply, include run-off from all surfaces, including off-site ones. Create a plan view drawing that delineates every sub-water shed, then note potential run-off figures. Start by multiplying total square footage by .62 gal., the standard calculation for approximating run-off from a 1-inch storm. Adjust this figure using run-off coefficients for various surfaces, as listed in Figure 1. Runoff Coefficients of Various Surfaces. Finally, multiply this by volume according to month-to-month precipitation data for the area. This is the site's naturally occurring supply.

After supply is estimated, calculate demand. Start with the highest demand period, the plant establishment phase. Keep in mind that irrigation demand will decrease as plants mature. A one- to two-year establishment period is usually appropriate, depending on plant selection. Calculate the number of emitters required per plant based on water volume and delivery rate. Estimate the number of one-hour irrigation cycles required per week or month during the growing season, adjusting for turf or other plant dormant seasons, if applicable. Multiply number of plants by required irrigation cycles. Then, multiply this by square footage of planting area. This is the site's water demand. For an example of a water budget calculation for a yard in Arizona where average annual precipitation is 13.9 inches, see Figure 2. Water Demand Calculation for a Small to Medium Landscape in Prescott, Arizona.

The site's total moisture budget is estimated by combing supply and demand. Just as in a financial budget, when demand exceeds supply there is a deficit. When supply exceeds demand, there is a surplus. Optimally, the final landscape plan will fit the moisture budget exactly. This doesn't mean restricting a design to existing conditions. Design techniques let us manipulate design elements to increase supply and decrease demand.

3. Manipulate runoff through grading and earthworks.

The design process begins after a total moisture budget has been developed. The primary goal of this phase is to use design and planning to manipulate conditions that affect water supply and demand, freeing the design to meet desired planting requirements. Grading and earthworks help direct, capture, and retain run-off, adding it to the site's supply.

Conventional landscape techniques that can impact water supply include terracing with earth or retaining walls, building earth berms to capture and hold water in plant beds, and installing dry wells and French drains. Total hydrology planning integrates these with sustainable techniques such as on-contour swales, meandering drainage swales, and head-to-toe rock cheek dams. Manipulate run-off to targeted areas through finish grading to maximize soil saturation in plant beds, making for healthier plantings and encouraging mulch and microorganism participating in the soil nutrient cycle. Mitigate stormwater runoff by keeping it on-site or filtering pollutants from water before it leaves. Create moisture zones by manipulating moisture shed from hardscape and building roofs. Incorporating flat-bottom planting infiltration basins into designs not only delivers and retains moisture for plantings, but also creates natural catchalls for leaves and other debris that build soil.

Swales planted with appropriate species enabled us to increase the planting palette of a zero-energy demonstration home in Borrego Springs, California. These experimental, energy-efficient and sustainable production homes are located in an area consistently ranked as one of the hottest in the United States. Surrounded by 600,000-acre Anza-Borrego Desert State Park, the arid site enjoys expansive desert and mountain vistas, but gets just six inches of rain per year. The goal was to create a self-sufficient landscape requiring no supplemental irrigation after plant establishment. This initially gave the project an extremely limited planting selection. We expanded it by concentrating run-off into planted bio-swales, where absorbing tilled-biomass makes rainwater available to a greater number and diversity of species. Attractive rain chains on the structures celebrate water, while salvaged rock and boulders shelter plantings and merge the new landscape with its desert environment. Native, drought-resistant plants salvaged from construction require no potable water irrigation. When rain is scarce, stored rainwater is applied.

4. Select plants for optimum performance.

Just as building swales and directing run-off increases the supply side of the water budget, selecting native and well-adapted plants suitable to the environment reduces demand. Plant selection provides numerous opportunities to improve a landscape's ability to take advantage of irrigation from naturally occurring or manipulated run-off sources. Typical design adjustments made here include swapping, shifting, and eliminating plants to meet optimum irrigation allowable by existing field conditions.

To determine a baseline planting plan, revisit the preliminary plant list and plan, overlaying them with the site's total moisture budget, including supply gained through run-off manipulation. Take into account dry areas created by lack of water concentration as well as wet areas created by concentration. Of course, this includes all water sheds from adjacent landscape topography, sidewalks, patios, house, and other buildings on the site. Choose native and well-adapted plants that are good for habitat and relevant to regional ecology.

Put plants into hydro-zones, created when plants are grouped together based on irrigation requirements. Each drip irrigation circuit is cycled separately so that each plant zone is also a separate drip zone. For example, fruit trees would be one hydro-zone, native shade trees another. Their irrigation requirements and establishment periods vary. Plants in their appropriate hydro-zones get neither over- or under-watered.

A joint public library project between the Town of Prescott Valley and Yavapai College in central Arizona called for an exceptional level of understanding of local indigenous plants and environment. The architect oriented the site plan and building to an extinct volcano that dominates the town’s landscape and history. Accordingly, the landscape plan concept, materials, and planting schemes were driven by the hill’s geology and plant life. Incorporating aggressive rainwater collection and energy efficiency, the plan used a completely native plant palette supported by earthworks and salvaged native stone. After a two-year establishment period, these native plants will thrive solely on natural precipitation.

5. Create microclimates by manipulating solar variables.

Sun and shade are crucial components for creating on-site microclimates where habitat can thrive. Shade directly affects moisture retention and plant selections. Hot and dry areas are dominated by exposure to full or reflected sun, while shady areas can be created by vegetation and site walls, fences, and buildings. An obvious way to provide shade is through trees, but shrubs, small plants, and boulders play a relative role in shading a site. An easy way to significantly increase shade is to expand a building in a strategic location, such as

- Garage addition on west elevation
- Trees on east and west elevations
- Porches, outdoor rooms, or arbors planted with vines
- Green fences, green walls, and green roofs.

Inversely, take advantage of hot, sunny areas by planting full-sun natives. Cactus, agave, yucca, and acacias are some of the most interesting and sculptural plants on the continent, and they live here in the Southwest. Use them.

In Phoenix, Arizona, shade is a premium commodity much of the year. With 334 days of sunshine and average summer temperatures in the triple digits, designing shade into plans is a must for creating healthy landscapes. Mission Lane is a city redevelopment project comprised of nine, two- and three-story multi-family housing buildings oriented east-to-west and designed for passive solar heating and cooling. The courtyard spaces created between structures were shaded with native shade trees pushed away from south elevations to welcome winter sun. To shade the buildings in summer, we used dense vines on east and west elevations, as well as shade trees placed where space allowed. Shade-tolerant shrubs were planted on shady north elevations and heat-tolerant desert species on sunny southern ones. The result is a diverse, water-efficient landscape encompassing several microclimates including cool, shady and moist and hot, sunny and dry.

6. Build soil.

Soil is where all the elements of total hydrology planning come together. Conventional landscape design and maintenance treats soil merely as a growth medium. Seen as a means to an end, soil is treated as a passive, secondary receptacle for fertilizer and water, something necessary to get turf, trees, and shrubs to grow faster or better.

Actually, soil is by far the most important part of the water budget equation. When treated as a vital participant in healthy landscape, soil is a self-fertilizing system that uses water as efficiently as possible. Soil is composed of fragmented minerals in the form of rock, gravel, sand, silt, and clay. This essential structure of a given soil has bearing on its ability to hold and release moisture, thus support plant life. Landscapes can participate in the soil-building cycle by providing soil with plenty of organic material to break down, rainwater to aid and support microorganisms, and a design that provides time for the process to succeed. Basins designed in grading and earthworks planning collect leaves, duff, and water to be gradually integrated into the soil, where they are gradually broken down into important nutrients.

Soil should be tested for PH as well as the ratio of nitrogen, phosphorous, and potassium content present (NPK). Available ratio of NPK affects plant growth, though it is more important to fruit and vegetable production than traditional landscape plants. Living organisms in soil make all the difference in its moisture and nutrient content. Bacteria and microrrhizas (symbiotic associations between a fungus and the roots of a plant) live in the soil, breaking down organic matter and making nutrients available to plant life. Commercial, petrochemical-based fertilizers, herbicides, and pesticides eliminate these beneficial microbes. Microorganisms do their job much better when fed a good supply of rainwater.

Designs should call for planting beds to be finished with a top coating of organic mulch. Mulch accomplishes many tasks for a landscape. It controls weeds, holds moisture in soils, and insulates them from solar radiation. It feeds soil building as it rots by providing food for microorganisms as well as earthworms and other tunneling, aerating insects. Wood chippings are often readily available but any large, shredded, organic matter will do, as long as it is heavy enough to withstand wind.

7. Augment supply with active water catchment.

The most important component in boosting the supply side of the landscape moisture budget is active water catchment. This includes rainwater collected off of roofs, filtered, stored in below- or above-ground tanks, and re-distributed when needed by pump, gravity, or through an irrigation system. It also includes grey water reclaimed from domestic plumbing, including laundry, bathing, and kitchen water. Both increase control over water supply without requiring potable water sources.

Grey water can be used as irrigation water in some states and municipalities. Already popular as a supplemental irrigation water supply, it is a reliable source that can be put into earth works for plant beds. Grey water comes with some special considerations that require applying it to landscapes with discretion. Generally, the less contact it has with human activity, the better it is for landscapes. It is best not stored but applied immediately to soils that will absorb it quickly. Care should be taken to prevent use of grey water than contains chemicals from items such as bleach or sodium-based detergents.

Active rainwater catchment, or harvesting, systems are far better for landscape irrigation. In addition to providing plants vital nutrients free of chemicals found in municipal water, rainwater drives salts away from plant roots, creates soil-building environments, and eventually filters back to the water table. Rainwater collection systems consist of a water-shedding surface (usually a roof), gutters, downspouts, filtering system, and a catchment and storage device. More complex systems include monitors, pumps, and other equipment to aid in water delivery and integrate with irrigation and grey water systems. The primary difference from passive catchment is that active systems store captured water for re-use at times and volumes under your control.

To maximize active rainwater catchment in landscape design, dovetail it with passive techniques such as those already discussed here and integrate it with other water-delivery systems. Overflow may be directed to swales or planting beds where thirsty plants are placed. Tanks may be used to create shade and windbreaks. Rainwater systems may be tied into irrigation systems already in place.

Conclusion

Approaching landscape design through a total hydrology mindset has benefits that extend far beyond irrigation efficiency. When landscapes no longer require life support, the impacts on maintenance are profound. Healthy, regionally appropriate landscapes are inherently low-maintenance. Weak, decorative exotic plants that demand continuous care are replaced with species that create self-sustaining, regenerative habitat. Plants thrive on the delicious rainwater they love, instead of being overdosed with chlorinated municipal water. Soils regenerate nutrients through retained rainwater and by breaking down leaves and other organic material left alone to decompose. The vicious cycle of fertilization-weed control-fertilization is eliminated. Combined, these effects save time and money, in addition to water.

Looking again at the big picture, stormwater flow is mitigated and run-off that does leave the site is filtered of pollutants that would otherwise end up in wastewater systems, rivers, and other bodies of water. Most important, demand is eased on natural resources such as potable water supply.

Figure 1. Runoff Coefficients of Various Surfaces

Surface Area Use	Runoff Coefficient
Open Space	.39 - .84
Commercial	.89 - .93
Residential, Half Acre	.54 - .85
Parking, Paved Roads, Roofs	.98
Gravel Roads	.76 - .91

U.S. Soil Conservation Service, 1975

Figure 2. Water Demand Calculation for a Small to Medium Landscape in Prescott, Arizona.

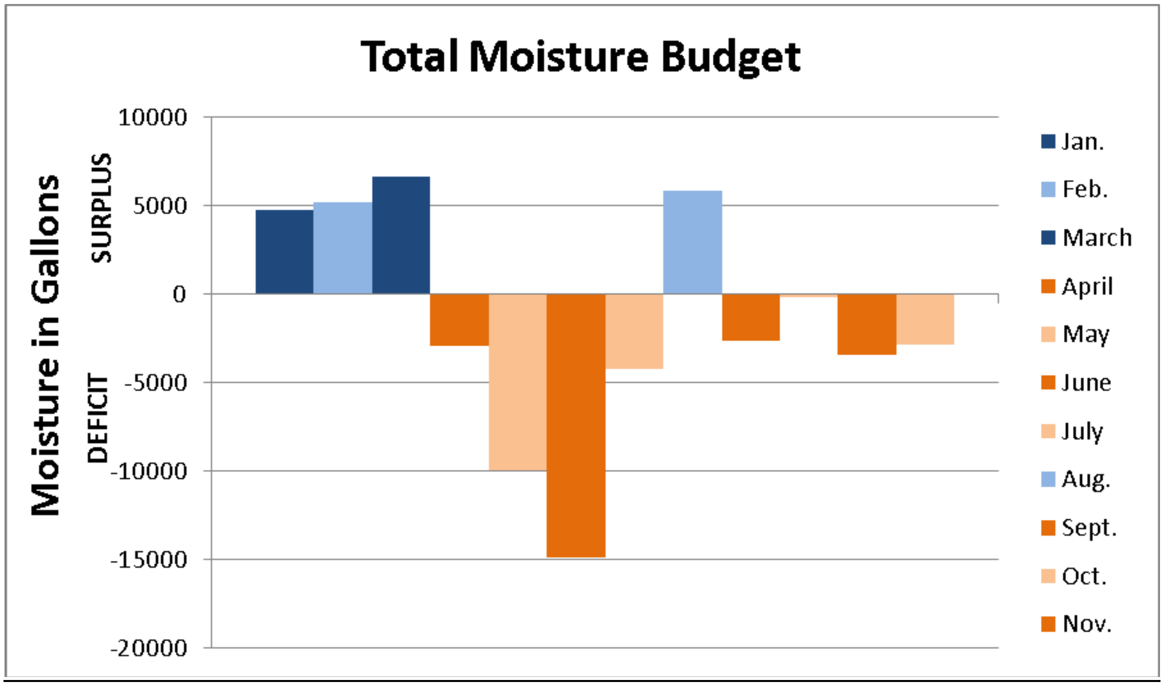
1. Calculate emitter per plant.
    1 gal. plant = 1, 1 gallon per hour emitter
    5 gal. plant = 2, 1 gallon per hour emitters
    15 gal. plant = 3, 1 gallon per hour emitters
2. Number of plants x irrigation rate.
    50, 1 gal. Plants = 1, 1 gallon per hour emitter = 50 gal./hr.
    30, 5 gal. Plants = 2, 1 gallon per hour emitters = 150 gal./hr.
    12, 15 gal. Plant = 3, 1 gallon per hour emitters = 180 gal./hr.
    Total Gallons per hour for this landscape = 380 gal.

3. Adjust for establishment period and seasonality.
    Summer (April through October)_
    1 time per week @ 2 hrs.
    760 gallons x 24 weeks = 18,240 gallons

    Winter (November through March)

1 time per month @ 2 hrs.
760 x 6 months = 4,560 gal.
Annual demand = 22,800 gal.

Figure 3.



Crop coefficients for drip-irrigated xeriscapes and urban vegetable gardens

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Abstract. *The decrease in water supply/demand ratios in the western U.S. is stimulating the region's municipalities to implement water conservation incentives. In response, many homeowners and businesses are replacing high water-using landscapes with drip-irrigated xeriscapes. Concurrently, due to concerns over food quality and safety, more home and community drip-irrigated vegetable gardens are being established in many of these municipalities. Unfortunately, due to a lack of adequate water-requirement information, these landscapes and gardens may receive inappropriate irrigation volumes required for acceptable plant quality and/or yield. This paper briefly describes research-demonstration projects that are developing climate-based (Penman-Monteith reference ET), canopy area-adjusted landscape or crop coefficients (*K_L *or* K_C*) for scheduling microirrigations in drought–tolerant landscapes and small vegetable gardens in northwestern New Mexico. Results indicated that an overall* K_L *of 0.3 would be appropriate for water management planning on xeric landscapes while canopy area-adjusted* K_C*s ranging from 0.6 to 0.9 provided maximum yields of tomatoes, chile peppers, and sweet corn.*

Keywords. crop coefficients, xeriscape, chile, tomato, sweet corn, irrigation, reference evapotranspiration

Introduction

The population of the southwestern U.S. and the concurrent demand for the limited water supplies of the region has increased dramatically over the past 50 years. As a result, many municipalities in the region have implemented incentives to insure that adequate fresh water be available to satisfy this rising demand. Incentives have included increasing-block water rate structures, water-use restrictions, penalties for water waste, or cash rewards for removal of high water-use landscape plants such as turfgrass. In response, urban landscapes in the west are increasingly being converted from sprinkler-irrigated, imported turfgrass lawns to drip-irrigated xeriscapes consisting of native plants or plants more suitable to the arid or semi-arid environments typical of the region. While this measure has the potential to conserve water, savings may not be realized if irrigation management strategies are not developed that match irrigation volumes to the water required by each plant to exhibit acceptable growth and quality in the xeriscape.

Water conservation in landscaping is not the only concern of southwestern U.S. municipalities and citizens. There has also been an increasing interest recently in local food production and food safety and quality. *Salmonella* spp. and *E.coli* outbreaks, along with inferior quality and taste of imported produce have instigated a resurgence of home vegetable gardens for household consumption and for sale at increasing numbers of local farmers markets. If expensive domestic water is used to irrigate these vegetable gardens, water conserving techniques such as drip irrigation and efficient irrigation scheduling must be implemented to minimize water-use while sustaining optimum yields and/or economic returns.

It's possible that in both of the 'non-standard' situations above, climate-based irrigation techniques may be used to effectively manage irrigations. In climate-based irrigation scheduling, a crop's water requirement or evapotranspiration (ET_C) is estimated by the product of a reference ET (ET_{REF}), calculated from weather data, and an experimentally derived crop coefficient (K_C). Typically, ET estimates and accurate K_Cs are formulated under standard conditions where the crop is grown in large monocultures that are disease-free, well fertilized, grown under optimum soil water conditions, and which achieve full production under the given climatic conditions (Allen et al., 1998). Landscape plants are usually isolated or separated from neighboring plants by greater distances than that of row crops and acceptable quality, rather than full production, is the primary goal. Small garden plots represent somewhat isolated, heterogeneous plant communities that, like mixed-species xeriscapes, do not exhibit 'standard conditions' since the aerodynamic characteristics of these small plots may be quite different than those of a large cropped monoculture.

Additionally, most published K_Cs have been derived from cropped fields in which the entire soil surface is wetted by sprinkler or flood irrigation. Early in the growing season of plants, ET_C is limited by each plant's small, live-leaf canopy area. Consequently, the K_C or ratio of ET_C to the climate driven ET_{REF} (ET_C/ET_{REF}) is small but then increases gradually as the crop's live-leaf canopy area as a percentage of total ground area, increases. If the entire soil surface is wetted during this establishment period, soil evaporation exceeds plant transpiration in ET_C until the soil surface dries. In drip irrigation, the evaporation component of ET_C is much less, since only a small area of soil around the base of each plant is wetted. Because of this, using recorded K_C values (or curves) to estimate the water requirement of individual plants of a given species when the plant is drip irrigated and is not a component of a large monoculture becomes difficult. A problem with using a programmed K_C curve over a canopy-adjusted K_C was pointed out by Hartz (1993) who concluded that over-irrigation of tomatoes can potentially result if using a programmed K_C over a canopy-adjusted K_C when crop development is slower than expected. In this case, crop ET might be better estimated by using a constant K_L or K_C and a variable per plant, live leaf canopy area. The use of a variable per-plant canopy area with a formulated constant K_C may help compensate for non-standard conditions such as variability in plant spacing, varietal differences, plant vigor and other factors that can affect canopy area.

Specific objective of these studies were to evaluate the effects of drip irrigation on the growth and quality of various drought tolerant landscape plants and on the yield of chile peppers, tomatoes, and sweet corn grown in small plots in an effort to formulate K_C constants under variable, single-plant crop canopy area estimates for scheduling irrigations on these plants when drip irrigated.

Materials and Methods

Studies were conducted from 2004 thru 2009 at New Mexico State University's Agricultural Science Center at Farmington, NM (ASCF). The ASCF is located on a high mesa (5,640 feet above mean sea level) overlooking the San Juan River in the northwest corner of the state. The site is semiarid, receiving an average annual precipitation of 8.2 inches. The soil classification at the study sites is a Kinnear very fine sandy loam soil (Typic Camborthid, fine loamy, mixed, calcareous, mesic family).

Daily Penman-Monteith reference ET for tall canopies (ET_{rs}) was calculated from daily maximum and minimum air temperature (^{o}C), daily minimum and maximum relative humidity (%), daily solar radiation (MJ $m^{-2}d^{-1}$), and average 24-hour wind speed (m s^{-1}) recorded at an automated weather station (Campbell Scientific, Inc. Model CR10) located less than 300 feet east of the plots using the ASCE-EWRI standardization procedures documented by Snyder and Eching (2004). ET_{rs} was then converted to English units for this paper.

Landscape Plants

A xeriscape demonstration garden consisting of more than 90 drought tolerant perennials having potential for use in urban landscapes was planted in 2002. The garden was split into four quadrants and at least one individual of each species was planted in each quadrant (Figure 1). Most of the specimens were transplanted from small starts (2 to 4 inch pots) obtained from a native plants nursery. All plants were irrigated uniformly for establishment until August 2003 when drip irrigation treatments were initiated and each quadrant received a different level of weekly irrigation (0, 20, 40, or 60% of ET_{RS}) or treatment factor (TF).

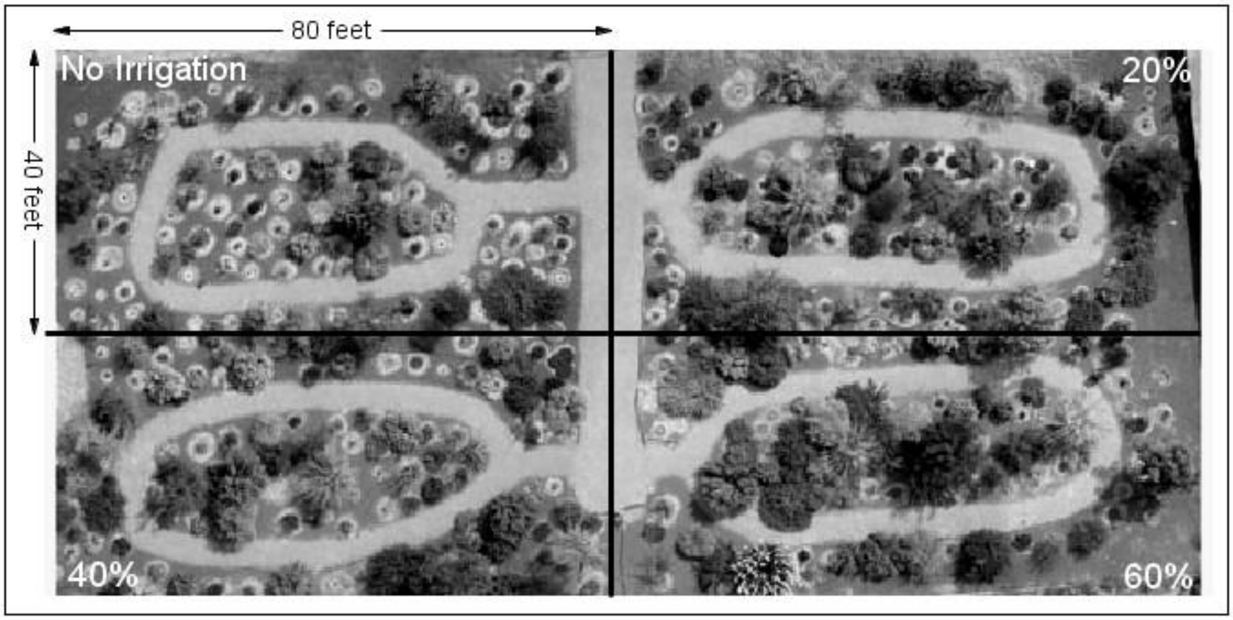

Figure 1. Overhead view of the demonstration garden used to estimate landscape coefficients (K_L) for various xeric-adapted plant species at NMSU's Agricultural Science Center at Farmington. Values represent irrigation as percentages of ET_{RS} times an average plant canopy area of 12.5 ft^2.

From 2004 thru 2009, a mean per plant canopy area (CA) of 12.5 ft^2 (4 ft diameter) was used to schedule irrigations on all plants using Equation 1. Adjustments were then made based on the actual measured plant CA in the lowest irrigation quadrant (minimum TF) where acceptable plant quality was observed for each species to derive a suggested landscape coefficient (K_L) for that species. Since water in most municipalities is billed by volumetric units, irrigation requirements are expressed in gallons.

Equation 1: Calculation of irrigation volume for treatments.

$$\mathbf{I = (ET_{RS} - P_E) \times TF \times CA \times 0.623}$$

Where:

I	irrigation applied, gallons per plant (gpp)
ET_{RS}	sum of daily Penman-Monteith reference ET values for tall canopy since last irrigation, inches
P_E	effective precipitation since last irrigation (60% of the sum of per event amounts greater than 0.2 inch), inches
TF	treatment factor (0, 0.2, 0.4, and 0.6 in xeriscape; re. Table 1 for vegetables)
CA	canopy area per plant in square feet (D^2 x 0.785); where D = plant diameter in feet
0.623	conversion factor for gallons/sq ft from inches

Vegetable Garden

For the vegetable crops, chile pepper, tomato, and sweet corn were planted in alternating block or randomized block designs with varying drip irrigation as treatments (Table 1) and the mean measured live (variable) canopy area per plant was used to schedule irrigations. Planting and plot information are shown in Table 1. In all years, the chile and tomato were planted in late May or early June from 1-in^2 transplants received from a local nursery. In 2005, these transplants were planted by hand but from 2006 thru 2009, a mechanical, tractor-drawn transplanter was used. Sweet corn seed was planted by hand about 1 to 2 weeks after the tomato and chile in all years.

Table 1. Planting and plot information for the studies designed to evaluate the effects of irrigation on the yield of chile pepper, tomato and sweet corn from 2005 thru 2009.

		YEAR				
	Crop[1]	2005	2006	2007	2008	2009
Planting Dates	C	9 June	23 May	7 June	2 June	N/A
	T	N/A	24 May	7 June	3 June	19 May
	SC	17 June	1 June	20 June	12 June	N/A
Plot Size (sq. ft.)	C	216	204	204	272	N/A
	T	N/A	204	204	272	151
	SC	216	204	136	272	N/A
Row Spacing (in.)	all	36	34	34	34	32
Plant Spacing within Row (in.)	C	18	12	12	12	N/A
	T	N/A	24	24	24	28
	SC	12	12	12	12	N/A
Plants/1000 square feet	C	222	353	353	353	N/A
	T	N/A	177	177	177	159
	SC	333	353	353	353	N/A
Replicates	all	3	3	3	4	4
Irrigation Treatments (Percent of ET_{RS})	C	100, 75, 50	105, 85, 65	100, 75, 50	85, 70, 55	N/A
	T	N/A	105, 85, 65	100, 75, 50	105, 90, 75	72, 80, 88, 96
	SC	100, 75, 50	105, 85, 65	100, 75, 50	85, 70, 55	N/A
Final Harvest Date	C	21 Oct	20 Sep	3 Oct	3 Oct	N/A
	T	N/A	12 Sep	3 Oct	1 Oct	17 Sep
	SC	8 Sep	17 Aug	6 Sep	6 Sep	N/A

[1] C – chile pepper, T – tomato, SC – sweet corn

Specific materials and methods for both of these studies, including plot plans, itemized irrigation and fertilization, harvesting dates and techniques, etc. can be found by referring to the Annual Progress Reports of the ASCF at the center's website: http://farmingtonsc.nmsu.edu (Projects and Results).

Irrigation

Establishment Periods

During establishment (2002 and early 2003) the plants in the xeric plant garden were irrigated with between 0.25 and 3 gallons of water per week. Irrigation frequency and amount within this range varied with plant size, age and atmospheric demand. Generally, newly planted specimens from 2 to 4 inch pots were irrigated every other day with about 1 quart of water per application during the first few weeks. As the plants became established and new growth was evident, irrigation frequency was reduced to once or twice per week and irrigation volume increased to between 1 and 3 gallons per application.

In all years except 2009, the vegetable garden area was irrigated uniformly with a sprinkler system to bring the top 2 feet of the soil profile up to field capacity (approximately 1.5 inches per foot) prior to planting. Two or three additional light sprinkler irrigations (less than 0.5 inch) were applied until the drip system could be assembled. These depth measurements, along with effective precipitation depths were converted to gallons per plant and have been added to the water applied in Table 3, Table 4, and Table 5. In 2009, the drip system was constructed immediately after planting. To insure successful establishment of the transplants, they were irrigated uniformly with the drip system at a K_C of 2.0 (due to the oasis effect) and a wetted area per emitter of 0.8 feet for the first 2-3 weeks after transplanting.

Irrigation Treatments

After the 2-3 week establishment period, the water volume applied per plant per irrigation (I) at the various treatments in both the xeric demonstration garden and the vegetable gardens was calculated using Equation 1. The landscape species were irrigated once per week from about mid-April to mid-October. The chile and tomatoes were irrigated every 2 to 3 days from about mid-June to final harvest (Table 1).

Results and Discussion

Reference ET

Total ET_{rs} during the 2005 thru 2009 growing seasons (April 1 thru October 31) averaged 66.5 inches. Daily ET_{rs} increased from about 0.24 inch in early April to 0.38 inch in mid June but varied widely from day to day during the spring due to significant fluctuations in temperature and wind (Figure 2). Average ET_{rs} then decreased gradually from 0.38 inch in late-June to about 0.16 inch in late October. The day to day fluctuation was much less due to more stable weather conditions in summer and early fall.

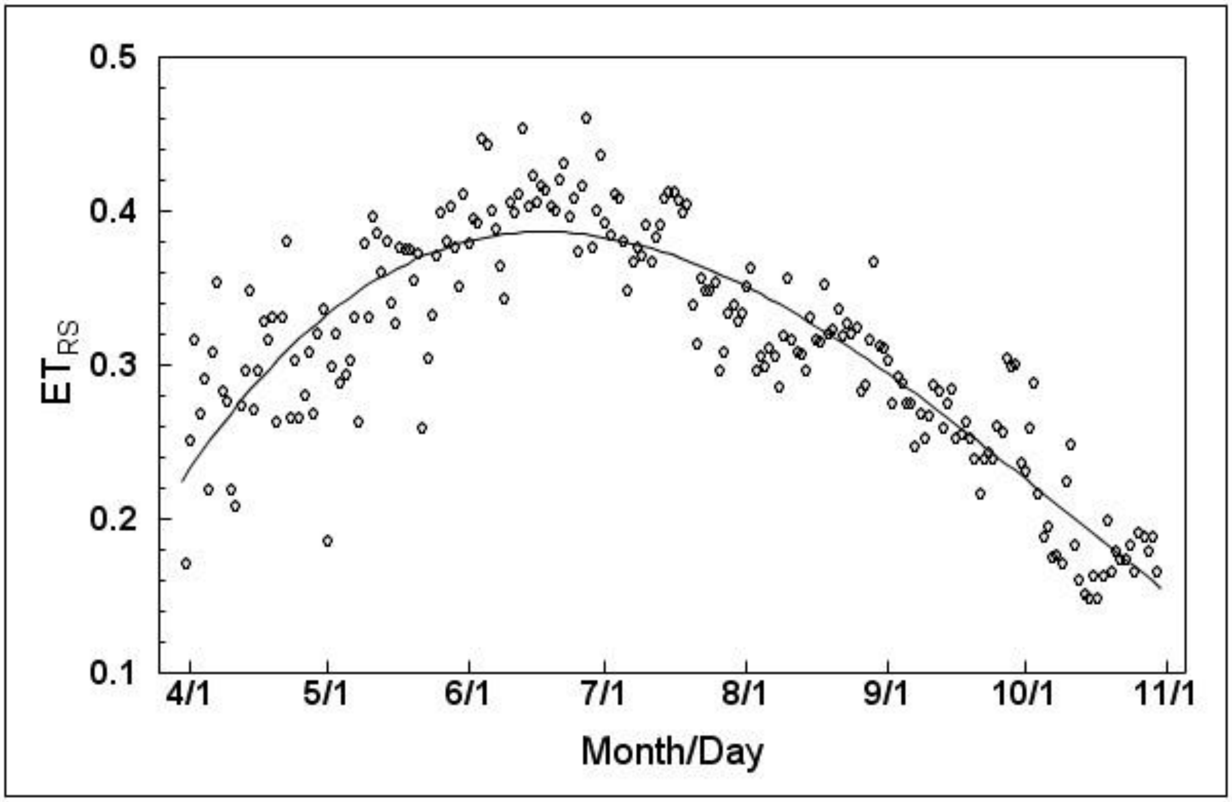

Figure 2. Average daily ET_{rs} between April 1 and October 31 during the five year period 2005-2009 at the ASC Farmington.

Xeric Plant Demonstration Garden

Suggested constant K_L values for plant species in the xeric plant garden, considering measured, variable plant CA and quality observations at the four different drip treatments, ranged from 0.05 for plants that exhibited acceptable quality in the zero irrigation quadrant (average annual effective precipitation of 3.0 inches) to 1.26 for a relatively small plant (*Echinacea purpurea*) that did well only in the quadrant receiving the highest irrigation (Table 2). The recommended irrigation requirement (IR) for each plant (Table 2) was then calculated using Equation 2.

Equation 2:

$$IR = ET_{RS} \times K_L \times D^2 \times 0.49$$

Where:

IR = irrigation requirement per plant, gallons (assuming no rain)
ET_{RS} = total P-M tall canopy reference ET since last irrigation, inches
K_L = landscape coefficient derived from minimum acceptable TF and actual CA
D = measured plant diameter, feet
0.49 = constant for conversion (inches to gallons and plant diameter to CA)

Table 2. Sample list of species in the xeric plant demonstration garden with canopy diameter (D), suggested landscape (crop) coefficient (K_L), and recommended weekly irrigation requirement per plant (IR) after five years of growth based on observed plant quality at four different levels of drip irrigation.

PLANT SPECIES	D	K_L	IR PER WEEK[†]
	feet		gals/plant
Artemisia tridentata (big sagebrush)	5.0	0.05	1.6
Berlandiera lyrata (chocolate flower)	2.5	0.05	0.4
Buddleja davidii (butterfly bush)	3.5	0.42	6.2
Caryopteris clandonensis (blue mist spirea)	4.0	0.24	4.6
Cerastium tomentosum (snow in summer)	2.5	0.78	5.8
Cercocarpus montanus (true mtn. mahogany)	5.0	0.11	3.4
Chilopsis linearis (willow-leaf catalpa)	8.0	0.05	4.0
Echinacea purpurea (purple coneflower)	2.5	1.26	9.4
Fallugia paradoxa (Apache plume)	4.0	0.05	1.0
Forestiera neomexicana (New Mexico olive)	5.0	0.05	1.6
Helianthus maximiliani (Maximilian sunflower)	5.5	0.30	11.0
Hesperaloe parviflora (red yucca)	4.0	0.15	2.8
Agastache foeniculum (blue giant hyssop)	2.5	1.02	7.6
Amelanchier utahensis (Utah serviceberry)	6.0	0.05	2.3
Caragana arborescens (Siberian peashrub)	4.5	0.05	1.3
Centranthus ruber (Jupiter's beard)	3.5	0.36	5.3
Chamaebatiaria millefolium (fernbush)	5.0	0.05	1.6
Gaillardia aristata (blanket flower)	3.0	0.64	6.9
Juniperus scopulorum (Rocky Mountain juniper)	4.5	0.13	3.1
Koelreuteria paniculata (goldenrain tree)	6.5	0.12	6.3
Penstemon ambiguus (bush penstemon)	4.0	0.05	1.0
Prunus besseyi (western sandcherry)	5.0	0.14	4.3
Hylotelephium telephium (autumn joy sedum)	3.0	0.39	4.2
Penstemon strictus (Rocky Mountain penstemon)	3.0	0.55	6.0
Penstemon "abuelitas" (Abuelita penstemon)	2.5	0.29	2.2
Rhus trilobata (3-leaf sumac)	5.0	0.11	3.4
Perovskia atriplicifolia (Russian sage)	4.5	0.13	3.1
Yucca baccata (banana yucca)	3.5	0.05	0.8
Sporobolus wrightii (giant sacaton)	5.0	0.17	5.2
Zinnia grandiflora (desert zinnia)	2.5	0.53	4.0

[†] Assuming no rain. If rain occurs during the week (or period), subtract 60% of the sum from events greater than 0.2 inch from ET_{rs}.

Vegetable Garden

Table 3, Table 4 and Table 5 show the total water applied per plant and marketable yields of chile peppers, tomato and sweet corn, respectively at the different irrigation treatments during four years of study. ‘Rowpac’ tomatoes were not planted in 2005 and neither ‘Big Jim’ chile nor sweet corn was planted in 2009. Two suggested constant K_C values for scheduling irrigations on each vegetable crop are also shown. The mean of the conservative K_C values shown in the ‘ANOVA’ column is suggested for use where water availability may be restricted or expensive and there is a probability that no further increase in yields will be provided at higher irrigation levels. The more liberal mean K_C shown in the ‘Max Yield’ column is suggested for use where availability of water is not limited or excessively expensive and the grower wants to insure a higher probability of producing maximum yields.

Chile peppers

Chile yield increased with irrigation level in all years except 2006 in which an inverse, but not statistically significant, relationship occurred (Table 3). This lack of response to irrigation in 2006 may have been due to a premature end to the growing season by an early frost that occurred on 23 September. In 2005, 2007, and 2008, statistical ANOVA indicated no significant difference between marketable chile yields produced at the high and medium irrigation treatments (Table 3). The relatively low yields in 2005 were due to a 15% loss of plants and delay in plant growth after planting due to curly top virus. The average suggested K_C values for irrigation scheduling on ‘Big Jim’ chile peppers were 0.71 and 0.88 for the conservative and more liberal scenarios, respectively.

Table 3. Yields of ‘Big Jim’ chile peppers at various drip irrigation treatment levels (TF) and suggested K_C values for scheduling drip irrigation based on ANOVA and maximum yield each year.

	TF	WATER APPLIED	MKT. YIELD†	SUGGESTED K_C BASED ON…	
Year	I/ET_{RS}	gals/plant	lbs/1000 sq ft	ANOVA	Max Yield
2005	1.00	47	743.8 a		1.00
	0.75	40	537.2 ab	0.75	
	0.50	34	427.0 b		
2006	1.05	50	803.5		
	0.85	42	840.2		
	0.65	34	932.0	0.65	0.65
2007	1.00	48	1147.8 a		1.00
	0.75	39	1092.7 a	0.75	
	0.50	31	835.6 b		
2008	0.85	32	1271.8 a		0.85
	0.70	27	1005.5 ab	0.70	
	0.55	22	775.9 b		
			Mean K_C	**0.71**	**0.88**

†ANOVA: Yield values within a year followed by the same letter are not significantly different from each other at the 5% level of confidence based on Tukey's HSD means comparison. The absence of letters indicates no significant difference in yields between treatments within the year.

Tomatoes

No statistically significant difference was found between tomato yields at the different irrigation treatments within any of four years (Table 4). The suggested average constant K_C for scheduling drip irrigations on tomatoes using Equation 2 ranged from 0.57 (based on ANOVA) to 0.77 at plots where maximum yield was observed (Table 4). The lower irrigation amounts and marketable yields of 2006 and 2007, as compared to 2008 and 2009, reflect reduced growth and canopy area in 2006 and 2007 due to disease.

Table 4. Yields of 'Rowpac' tomato at various drip irrigation treatment levels (TF) and suggested K_C values based on ANOVA and maximum yield each year.

		IRRIGATION	**MKT. YIELD†**	**SUGGESTED K_C**	
Year	**TF**	**Gals/plant**	**(lbs/1000 sq ft)**	**By ANOVA**	**By Max Yield**
2006	1.0	43	1455		
	0.75	36	1524		0.75
	0.50	28	1336	0.50	
2007	1.0	48	1263		
	0.75	39	1276		0.75
	0.50	31	909	0.50	
2008	0.85	77	2433		0.85
	0.70	64	2231		
	0.55	51	2218	0.55	
2009	0.96	93	3880		
	0.88	85	3880		
	0.80	78	3770		
	0.72	70	4178	0.72	0.72
			Mean K_C	**0.57**	**0.77**

†ANOVA indicated no significant difference in yields between treatments within any year.

Sweet corn

Maximum yield of sweet corn occurred at the highest level of irrigation (mean K_C = 0.95) in all four years (2005 thru 2008) of study but ANOVA indicated no statistically significant difference between yields at all three irrigation treatments in 2005 nor between the high and medium irrigation treatments in 2006, 2007, and 2008 (Table 5). The average suggested constant K_C values for scheduling irrigations were 0.68 based on ANOVA and 0.95 based on maximum observed yield (Table 5).

Table 5. Yield of sweet corn at various drip irrigation treatment levels (TF) and suggested K_C values based on ANOVA and maximum yield each year.

		IRRIGATION	YIELDS PER 1000 SQ FT		SUGGESTED K_C	
Year	TF	Gals/plant	No. Ears	lbs*	By ANOVA	By Max Yield
2005	1.00	29	611	354		1.00
	0.75	26	540	298		
	0.50	23	537	303	0.50	
2006	1.00	33	690 a	303 a		1.00
	0.75	30	618 a	266 ab	0.75	
	0.50	27	521 b	211 b		
2007	1.00	33	603 a	285 a		1.00
	0.75	26	584 a	275 a	0.75	
	0.50	20	422 b	174 b		
2008	0.80	28	622 a	340 a		0.80
	0.70	24	584 ab	321 ab	0.70	
	0.60	20	554 b	298 b		
				MEAN K_C	**0.68**	**0.95**

†ANOVA: Yield values within a year followed by the same letter are not significantly different from each other at the 5% level of confidence based on Tukey's HSD means comparison. The absence of letters indicates no significant difference in yields between treatments within the year.

Conclusion

Irrigation studies were conducted in an effort to develop drip irrigation scheduling coefficients for drought-tolerant landscape plants (K_L) and three vegetable crops (K_C) commonly grown in small gardens in northwest New Mexico. The xeriscape demonstration garden, with its differentially irrigated quadrants, conveyed some valuable information on the potential growth and quality of more than 90 species of plants at various levels of drip irrigation. While there was considerable variability between suggested K_L values for the different species, an overall K_L of 0.3 is suggested for estimating the water requirements of a mixed-species xeriscape. This is considerably lower than the commonly cited K_L values of 0.6 and 0.8 for warm season and cool season turfgrasses at full green canopy, respectively. Since live canopy area (CA) is an element of the computational procedure for estimating the ET_C or irrigation requirement of all plants, a constant K_L is suggested for use throughout the entire growing season. This is in agreement with the procedures used in California's 'Water Use Classification of Landscape Species' (WUCOLS) guide (Costello and Jones, 1994).

There was also considerable variability in the K_C values of vegetable crops both between species and between years. Conservative mean constant K_C values were 0.57, 0.68, and 0.71 for tomato, sweet corn and chile, respectively, but maximum yields were observed at more liberal mean K_C values of 0.77, 0.95, and 0.88 for the respective crops. As in the xeriscape study, the same procedures for calculating drip irrigation treatments and formulating K_C values and estimating irrigation requirements were used; that is, a single constant K_C for the entire growing season was used with variable live per plant canopy area in the equations. This method has some advantages over the commonly published K_C curves that exhibit a linear increase in K_C during the crop development stage and then a linear decline in late season (Allen et al., 1998), in that it compensates for non-standard conditions such as variability in plant spacing, plant varietal differences, plant health, and other factors which may affect live canopy area.

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The Inherent Drought Response Flexibility in Irrigated Landscapes

by

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ABSTRACT

Many western U.S. landscapes can be typified by irrigated areas in turf grasses, shrub beds, trees in turf grasses, and vegetable gardens. The irrigation systems can be typified as sprinkler irrigation systems, or often combination drip and sprinkler systems, with sprinklers used in appropriate turf areas and drip irrigation used in shrub beds. Generally, if these irrigation systems are properly designed, then there is clear distinction with individual laterals irrigating either turf grass or shrub beds.

The water for irrigation is often potable but it can be raw water that is continued to be used for its decreed purpose, namely irrigation. In many parts of the country, the demands of landscape irrigation can be nearly 50 percent of the total annual potable water demand. Because landscape demand is seasonal, the peak season water treatment needs are in effect driven by the landscape irrigation.

Under drought circumstances, supplies are limited and reductions must be made. Typical drought responses include odd-even day irrigation, a proscribed number of irrigation days per week, or some other, blanket curtailment. Alternatively, many water purveyors increase unit cost and reduce demand in a punitive way. None of these methods take advantage of the drought-resilience or economic value of landscape elements in their "one-size-fits-all" approach to drought response.

Landscapes offer tremendous flexibility to adapt water applications to the severity of the drought and drought response plans can be formulated at various levels that are tied directly to the drought severity. For example, under a moderate drought it may be suitable to simply reduce applications to turf grass. Increasing levels of drought severity result in expansion of the drought response to other areas of the landscape, from turf to shrubs to trees.

Introduction

In various regions of the United States, water availability and seasonal water quantity issues are receiving unprecedented discussion, scrutiny, and attention from many perspectives. Landscapes and landscape irrigation are an important part of the

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discussion and often enough, the target of the discussion. Irrigation is often 45% to 55% of annual potable water deliveries based on numerous studies.

A short list of intertwined landscape issues includes:

- Amount of landscaped area, including the proportion of the turf grass area.
- Approach to landscape irrigation system -- the products, the control system, and water use efficiency.
- Sources of water and including the poignant question “should be irrigated with potable water?”
- Overall sustainability of the landscape.
- Adequacy of water supplies to include safe yield, quality, and losses in an aging infrastructure.
- Metering of water for irrigation.

In the past, and in the author’s view, the topic of outdoor water and the approach to landscapes has periodically seen elevated discussion, press coverage, and public attention. Those discussions have often been rather short lived. An example is the promotion of xeriscaping and xeriscape landscapes in the Denver area during the late 1970s. There was good public acceptance of the approach, and to saving water outdoors generally, but the duration of the discussion and active promotion of xeriscape was less than 10 years. As with xeriscaping, outdoor water savings and efficiency tend to ebb and flow much like the discussions of floods and droughts, respectively. Public attention is garnered and held most often when there is a crisis.

At present, we are seeing a national debate and base-level questions considering the amount of landscape and the amount of water that can be used for landscape irrigation. This paper attempts to frame an argument for some adjustment in our collective thinking about landscapes and landscape irrigation without dramatic impact on our valuable and much appreciated landscapes. This might be a good time for a paradigm shift to occur and settle in for the long term. Use of sound science and public education are part of a sustainable solution.

Landscape Water Requirements and Irrigation Scheduling

A great deal has been written about landscape water requirements and scheduling irrigations to effectively meet but not exceed the plant needs. The homeowner tenancy has long been, and still is, to over-irrigate landscapes because water is relatively cheap and the water bill still does not get much attention from homeowners.

The evapotranspiration rate is published daily in some areas and if the homeowner has that information at hand, and can relate it to the application rates of their system, then improved irrigation scheduling can be attained. The results vary widely and reports of successes are often tied to very in-depth communications and training with customers. Often enough, qualified irrigation contractor oversight becomes important in keeping home owners on a suitable track of scheduling irrigations to need.

A key factor in making landscapes more flexible is to have a complete understanding of the water requirements, the manner of water applications, and an understanding of where adjustments can be made for purpose. *This is the management component.*

The Landscape Irrigation System

The irrigation system is just that -- a system. The collective system consists of the myriad of valves, wire, pipes, controllers, and water emission devices (sprinklers, drip emitters, etc.). The system, if properly designed and installed, is assumed to be capable of irrigating the landscape to meet peak season water requirements using laterals that are tied, in a practical way, to “hydrozones” within the landscape. Assume for the purposes of this paper, that the landscape irrigation system is properly designed for the landscape, well maintained, and operationally flexible.

Auditing of landscape irrigation systems to understand the built system along with application rates and application efficiencies is now more accepted than ever before. In some areas, initial and periodic auditing of the system is required. The Irrigation Association has certified approximately 1,200 individuals as Certified Landscape Irrigation Auditors (often abbreviatated as “CLIA). Most of these individuals have also become WaterSense Partners within the EPA’s WaterSense program.

Control systems that underpin high efficiency irrigation include full-featured, multiple program, controllers having features such as “cycle and soak” that allow run times that are compatible with soil intake rates. The newer “smart” or climate-based controllers provide adaptation to changing water requirements. Sprinkler and emitters are preferred to be of the pressure compensating types.

The distribution uniformity (DU) is a sprinkler performance metric that has gained wide acceptance in the industry as a means of truly comparing sprinkler / pressure / nozzle alternatives at the design stage. Almost more importantly, DU can be field evaluated via an audit and using catch can data to ensure desired as-built performance.

It would appear that a system performance bar is being raised for landscape irrigation which will ultimately play out to the benefit of the homeowner, the water purveyor, and the irrigation industry. Water use efficiency is getting unprecedented attention and rightly so.

Relative to the topic of this paper, it is important that the irrigation design incorporate a suitable amount of operational flexibility to adapt to a drought response plan. What this may mean, is strict design and definition of hydrozones and possibly increased numbers of laterals if plant material water applications are to be tied ever so much closer to water availability.

This is the system component.

The Landscape

It certainly is not my intent to espouse on the merits of various plant materials or landscape design in this paper. That is not my area of expertise. However, there are characteristics that, especially when married up with the landscape irrigation system, provide the desirable flexibility for drought response.

These general characteristics include groupings of trees and shrubs, drought tolerant grasses, and manicured and irrigated turf grasses. The intent of the landscape design is very important and that intent simply needs to be balanced with a water budget to provide the desired flexibility. The landscape and the irrigation system, taken together, provide options and flexibility. Likely, the future holds a more thoughtful and water budgeted design to achieve needed flexibility.

The landscape and the irrigation system, taken together and functioning together, provide the flexibility. An example is shown in Figure 1 showing drip irrigated trees in otherwise unirrigated areas, drip irrigated trees and shrubs in a mulched shrub bed, and sprinkler irrigated turf grass (in this case bluegrass) for human activity.

This is the landscape component.

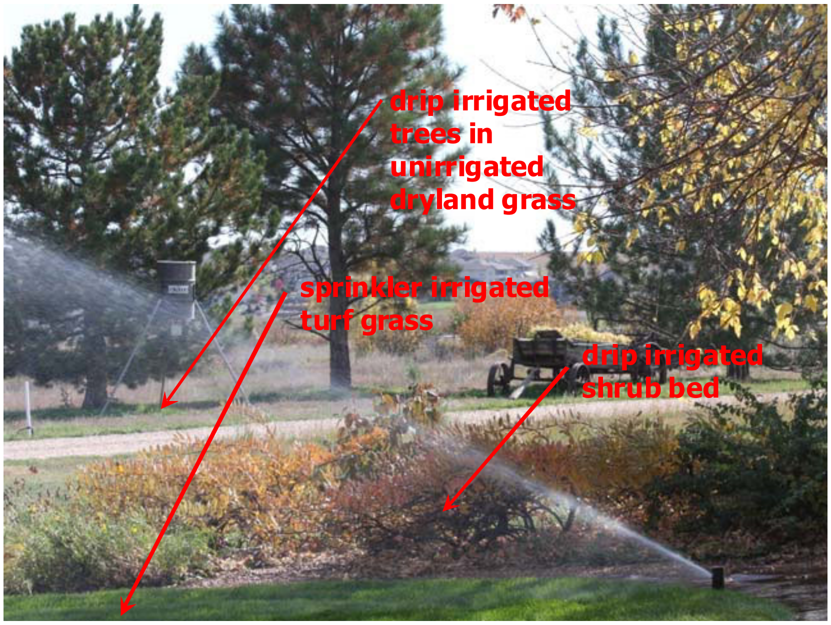


Figure 1. An example of desirable flexibility in an irrigated landscape.

Water Supply, Drought, and Drought Response

Water supply for municipal use is generally evaluated on the basis of “safe yield” which is a term that helps understand a water purveyors risk as associated with the variables in the supply. Fifty years is often the hydrologic period of record that is used. A community needs a projected annual supply to meet all the needs of the community and that would include projections of population change – population growth in most of the western U.S.

Drought does not have a single definition. It has been noted that we do not know when droughts start or end until you look back at the event. The threshold data could be precipitation or it could be stream flows. Stream flow is most often an indicator or drought in those areas having snow pack from which water supplies are derived.

An example is shown in Figure 2 for the Poudre River in northeastern Colorado.

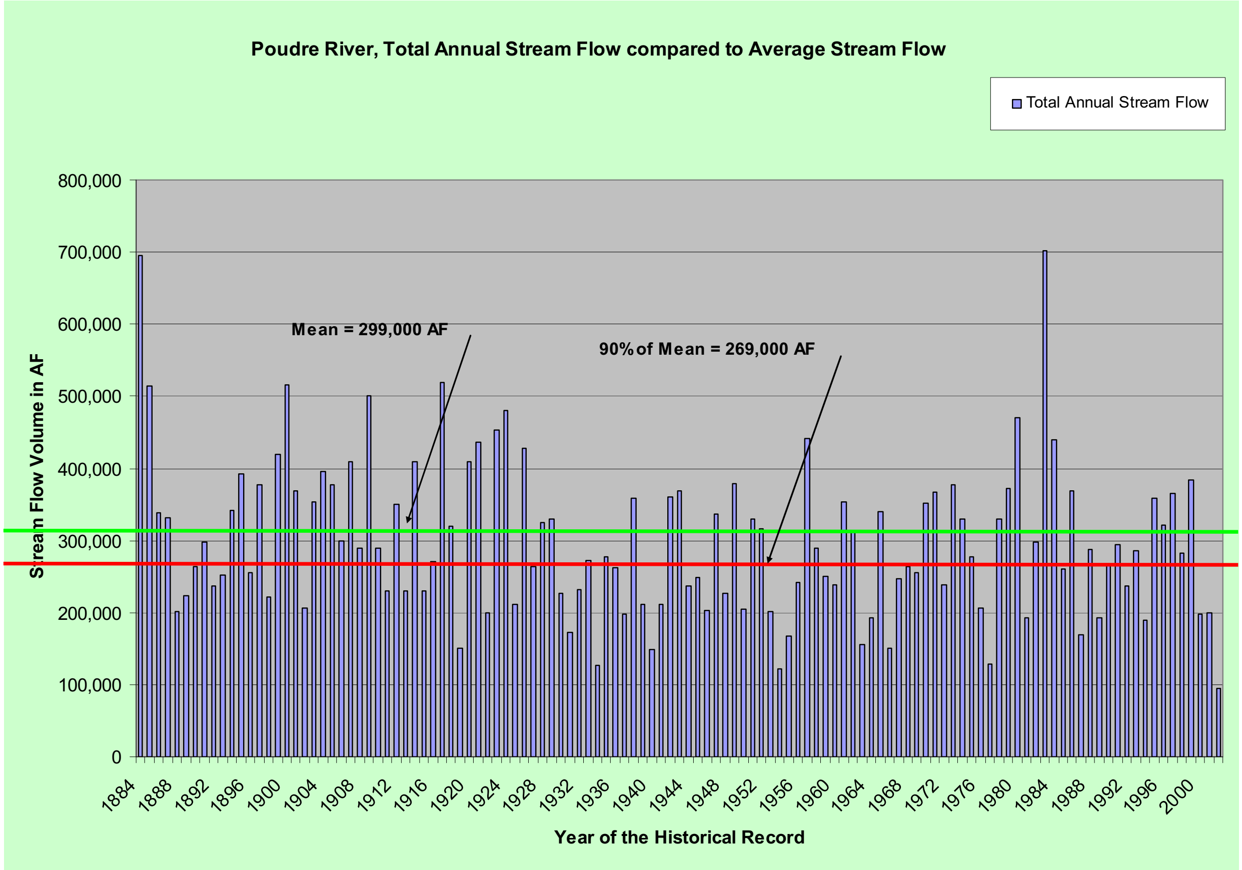


Figure 2. The variability in stream flow over a long period and indicative of the wet and dry periods of record. Reservoirs help capture excess flows in wet years for delivery in dry years and thereby provide needed flexibility to the potable water purveyor.

Clearly, the historic record for the Poudre River and many rivers is highly variable as shown in Figure 2. The droughts of the past tend to be those droughts that we plan for in the future. If reservoirs are a part of the water supply system, then reservoirs capture water in the wetter years to be delivered in the dryer years, thereby creating needed flexibility in the upstream delivery system.

This is the drought response and water supply delivery system component.

Responsible and Sustainable Landscape and Irrigation Operations

The overall premise here is that landscapes provide operational flexibility that we do not take full advantage of. Sure, if we are short of water due to drought or other supply concerns, our water purveyors, and we as customers, will decrease water applications. This can be driven by water purveyor mandates and "water cops" or it can be driven by punitive unit rates, including escalating water rate structures. Most generally, outdoor water use becomes the obvious target for reductions because of the large volume and because landscapes, stating the obvious, are clearly less important than human health and safety. Indoor culinary water, wash water, and sanitary water are a more important use of potable water than outdoor irrigation.

There is potential to dramatically decrease outdoor water applications and thereby chop the top off of the typical annual potable water delivery curve as shown in Figure 3.

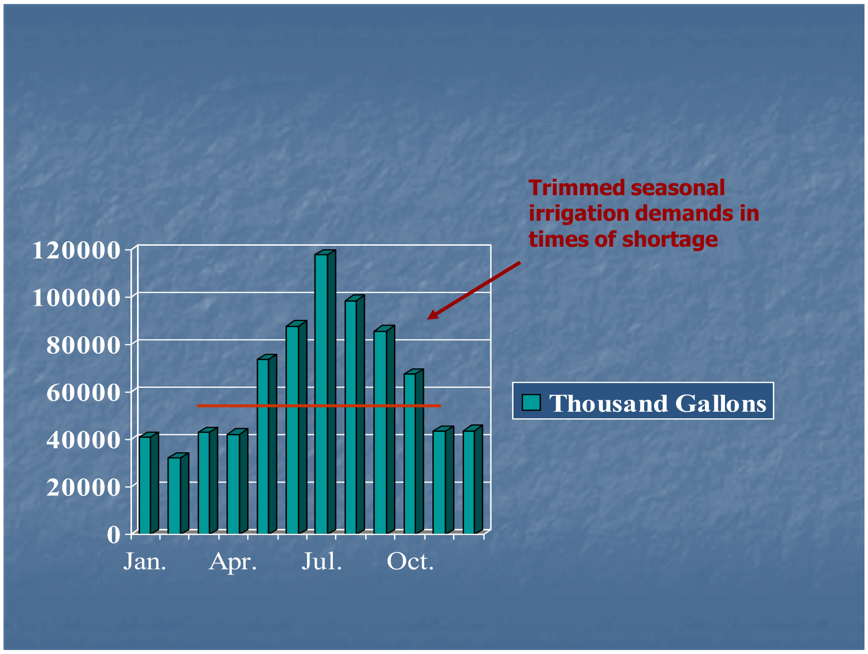


Figure 3. Many potable water purveyors see annual deliveries as shown with dramatically higher deliveries during the irrigation season. Reducing landscape water deliveries in times of drought will reduce the total annual delivery while also reducing the peak season water treatment requirements.

Figure 4 is a representation of two different but equally important aspects of managing water delivery systems in a flexible and sustainable way. On the upstream side of the delivery system, water storage is key to capturing water in wetter hydrologic years for delivery in dryer years. Likewise, on the downstream side of the distribution system, landscapes can be provided with less water than optimal for decreasing deliveries and saving reservoir storage. The overall delivery system can be managed for seasonally varying water availability circumstances.

Thresholds for action levels should be defined in a planning process and a drought response plan created that utilizes the flexibility in the landscape. An example of such a drought response plan is shown in Figure 5.

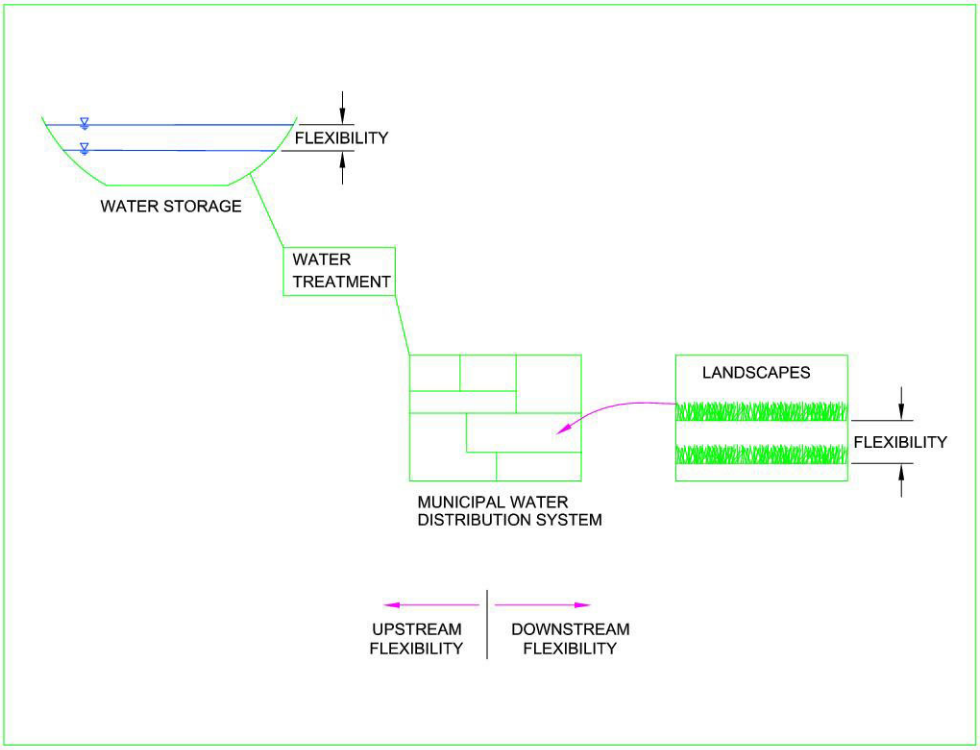
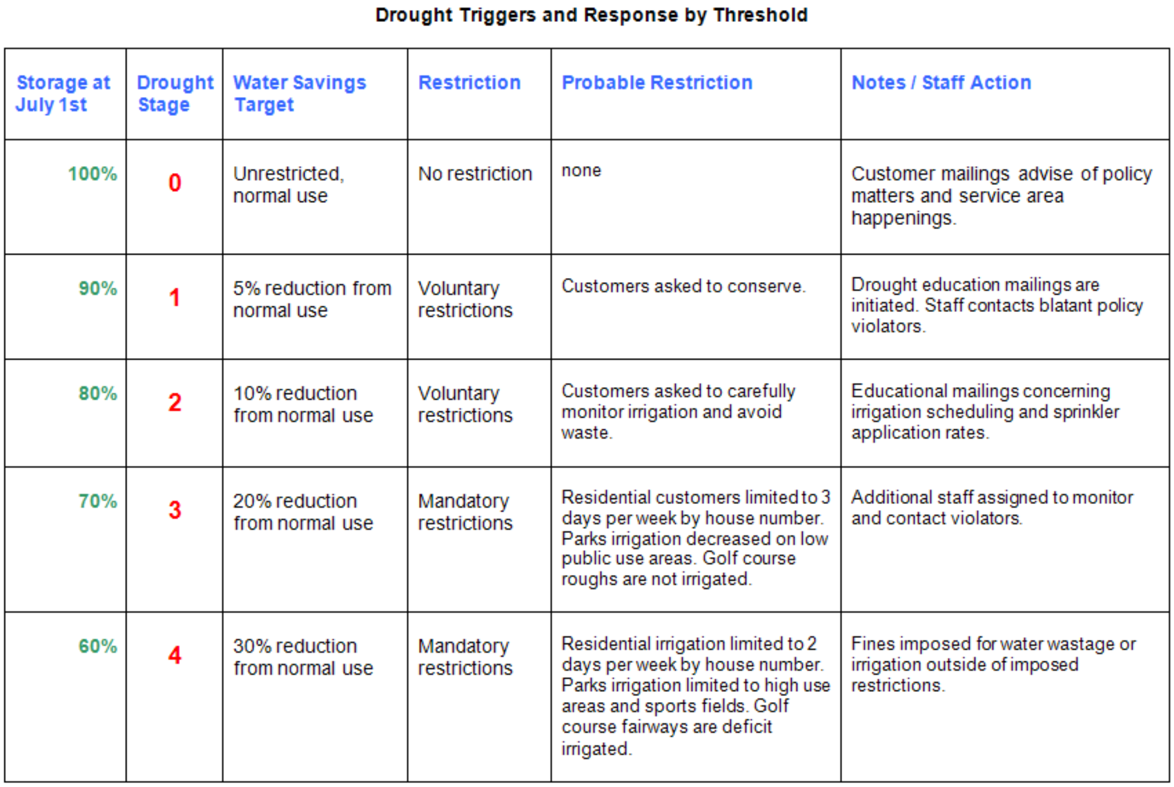


Figure 4. The potential to treat landscapes and water for landscapes as a flexible delivery in consideration of drought or other water short circumstance is diagrammatically shown. Just as a reservoir provides flexibility on the upstream delivery, landscapes can provide flexibility on the downstream delivery.



Drought Triggers and Response by Threshold

Storage at July 1st	Drought Stage	Water Savings Target	Restriction	Probable Restriction	Notes / Staff Action
100%	0	Unrestricted, normal use	No restriction	none	Customer mailings advise of policy matters and service area happenings.
90%	1	5% reduction from normal use	Voluntary restrictions	Customers asked to conserve.	Drought education mailings are initiated. Staff contacts blatant policy violators.
80%	2	10% reduction from normal use	Voluntary restrictions	Customers asked to carefully monitor irrigation and avoid waste.	Educational mailings concerning irrigation scheduling and sprinkler application rates.
70%	3	20% reduction from normal use	Mandatory restrictions	Residential customers limited to 3 days per week by house number. Parks irrigation decreased on low public use areas. Golf course roughs are not irrigated.	Additional staff assigned to monitor and contact violators.
60%	4	30% reduction from normal use	Mandatory restrictions	Residential irrigation limited to 2 days per week by house number. Parks irrigation limited to high use areas and sports fields. Golf course fairways are deficit irrigated.	Fines imposed for water wastage or irrigation outside of imposed restrictions.

Figure 5. An example of drought response triggers and varying thresholds that indicate corollary response actions is shown. This type of drought response plan is best accomplished as a relaxed planning exercise and should not wait until a time of crisis.

Summary

We all hear the word “sustainable” and “sustainability” a lot. One definition of sustainability is “the capacity to endure.” Irrigated landscapes can have the capacity to endure and survive short term drought events without long term repercussions. The primary elements that allow for this adaptation and successful operational flexibility are:

1) Landscapes: well designed landscapes that are characterized by plant materials selected with purpose and grouped appropriately so hydrozones can be defined. This is simply sound landscape and irrigation design.

2) Irrigation systems: well designed irrigation systems that utilize efficient equipment (pressure compensating devices and high distribution uniformity), smaller and adaptable laterals, appropriate hydrozones, and sound control and irrigation scheduling practices.

3) Deficit irrigation: understanding of the effects of deficit irrigating plants in the landscape and which plants, or plant groups, offer the most potential for reduced water applications in times of drought or other water shortage.

References

Smith, S.W. 1997. Landscape Irrigation: Design and Management. John Wiley & Sons, Inc., New York.

Using Radiation Thermometry to Assess Spatial Variation of Water Stressed Cotton

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Abstract. *The use of infrared thermometry and thermal imagery to investigate unapparent but important field conditions (poor drainage, non-uniform irrigation, soil variability, or biotic infestations) offers a producer improved management tools to avoid yield declines or variability in crop status. This study investigated spatial and temporal crop water stress based on crop canopy temperature extracted from remote thermal images and point infrared thermometry within the imaged area to calculate an empirical crop water stress index* ($CWSI_e$) *for varying levels of manually and automatically irrigated cotton (Gossypium hirsutum L.). The daily* $CWSI_e$ *calculated from canopy temperature data extracted from thermal imagery was significantly related to midday leaf water potential (LWP),* $r^2 = 0.88$ *in 2007 and* $r^2 = 0.77$ *in 2008. Data from 2007 indicated a significant inverse correlation between seasonal mean* $CWSI_e$ *values derived from infrared thermometry and yields,* $r^2 = 0.86$ *and 0.77,* $p< 0.001$*, for manually and automatically irrigated plots, respectively. In 2008, there was also an inverse linear relationship between* $CWSI_e$ *and yield for deficit irrigated cotton in the automatic blocks,* $r^2 = 1.0$*,* $p< 0.001$*. However, there was a positive correlation between* $CWSI_e$ *and yields in the manually irrigated plots. High temperatures and wind, and heavy rainfall near the period of boll maturation negatively impacted yields and the yield –* $CWSI_e$ *relationship. In the future, it is plausible that thermal imaging sensors combined with computational analysis will provide real-time spatial and temporal information concerning in-field crop water status.*

Keywords. Infrared thermometry, infrared imaging, crop water stress, spatial variation

Introduction

Remote sensing technologies have potential as tools for monitoring crop water status, improving water use efficiency, saving water, and precisely managing irrigation. Useful information on canopy water relations can be derived from infrared thermometry and thermography. Infrared thermography in agriculture has been used as a non-invasive versatile imaging tool to investigate biotic stress (disease or insect infestation), and abiotic stresses (e.g., nutrient and water deficit). Chaerle et al. (2006) combined thermal and chlorophyll fluorescence imaging to study spatial and temporal heterogeneity of leaf transpiration and photosynthesis. These techniques helped them to identify pre-symptomatic responses (higher chlorophyll intensity co-located with thermal symptoms) and provided diagnosis of diseases (fungal and bacterial infections) and abiotic stresses not yet perceptible in visible spectrum images. Stoll et al. (2008) used an infrared camera to observe thermal responses in grapevine infected with a fungus well in advance of visible symptoms.

Studies involving the analysis of abiotic stresses with thermal imagery include those by Jones (1999) and Jones et al. (2002) in which field studies were designed to assess the consistency and repeatability of using thermal imagery to measure stomatal conductance in grapevine canopies. They concluded that thermography allows for semi-automated analysis of large areas of canopy with much more effective replication than can be achieved with porometry. Leinonen and Jones (2004) classified thermal images to identify leaf area, and sunlit and shaded parts of the canopy. Their methods provided improved estimates of temperature distribution across a canopy by separating out mixed pixels and reducing the effects of thermal contribution from background. Möeller et al. (2007) used thermal and visible imagery to estimate the crop water status of irrigated wine grapes. Their tactic included using the temperature of an artificial wet reference to estimate a wet baseline (i.e., a surrogate for a fully transpiring leaf) and using the maximum daily air temperature to estimate a dry baseline, both of which were needed to calculate a crop water stress index (CWSI) value that was then related to LWP. Ben-Gal et al. (2009) evaluated water stress in irrigated olive orchards using remote thermal imagery to measure average crop canopy temperature and calculate the CWSI using an empirical and analytical approach. It was determined that there was no significant difference between the two approaches.

At the Bushland USDA-ARS Conservation and Production Research Laboratory, thermal imagery has been used to document the spatial variability of crop water status, separate temperature contributions from sunlit and shaded plants and soil, document temperature differences between drying grain and plant leaves, and estimate crop canopy cover in irrigated fields. An empirical crop water stress index, CWSI_e, was calculated as:

$$\mathrm{CWSI}_{\mathrm{e}} = \frac{T_c - T_w}{T_{dry} - T_w} \qquad [1]$$

where T_{c} was the temperature (°C) of the crop at the time of the thermometric image, T_{w} was the average temperature of a “wet reference” that acted as a substitute for the well-watered base line or lower boundary temperature. T_{dry} represented the upper boundary temperature and was estimated by adding 5°C to the maximum dry bulb temperature recorded (Möller et al., 2006) for the specific field day. This index ranges from > 0.0 since $\mathrm{T_c}$ is typically greater than $\mathrm{T_{wet,}}$ and can exceed 1.0 when the $\mathrm{T_c} > \mathrm{T_{dry}}$.

Additionally, infrared thermometers (IRTs) mounted on a center pivot irrigation system lateral have been used to remotely monitor soybean and cotton crop canopy temperature, and schedule automatic irrigations based on a thermal stress index (Peters and Evett, 2004). Our objective was to characterize in-field crop water status and estimate yields based on the $CWSI_e$. Initially temperatures extracted from the thermal imagery were used to calculate the stress index and compared to LWP. Scaled crop canopy temperature data (Peters and Evett, 2004) from the IRTs on the center pivot were used to formulate mean seasonal $\mathrm{CWSI_e}$ values.

Methods and Materials

Agronomy

Crop water status was controlled spatially by full and deficit irrigations applied to a semi-circle of concentric plots blocked arc-wise by irrigation method, either manual or automatic scheduling techniques (Fig. 1). Cotton (*Gossypium hirsutum* L.), variety Paymaster 2280[1] was planted on day of year (DOY) 149 (May 29) in 2007 and variety Delta Pine 117 B2RF[1] was planted on DOY 141 in 2008 (both varieties were Bollgard II® Roundup Ready®, Delta and Pine Land Co., Scott, Miss.). The crops were grown in eighteen row plots on beds spaced 0.76-m apart under a three span center pivot at Bushland, Texas (35˚ 11' N, 102˚ 06' W, 1174 m above mean sea level). Manual irrigations were applied weekly to three blocks, each comprised of four treatment plots and two replicates (Fig. 1). Irrigation was applied manually at levels of 33%, 67%, and 100% (treatments designated $I_{33\%}$, $I_{67\%}$ and $I_{100\%}$) of full replenishment of soil water in the root zone to field capacity based on neutron moisture meter readings and using low energy precision application (LEPA) drag socks. Dryland plots were also included as the fourth treatment ($I_{0\%}$). Irrigation treatments were applied in the northwest half of the field in 2008 and the southeast half of the field in 2007 with the unused half of the field supporting a cover crop each year in order to even out soil water differences caused by the irrigation treatments in the year before. The blocks labeled "auto" were irrigated using the time-temperature threshold (TTT) algorithms for irrigation automation and control that use canopy temperature measurements (Peters and Evett, 2004). The full irrigation level for automatic treatments was based on the peak week-long crop water use, previously evaluated at Bushland as 10 mm d^{-1}. Each time a TTT irrigation signal was recorded, a 20-mm irrigation was automatically applied (double the peak water use because automatic irrigations were applied only every other day so that manual irrigations could be scheduled on alternate days). A temperature and humidity sensor (model Vaisala HMP45C, Campbell Scientific, Logan, Utah) was mounted at the end of the pivot arm and wired to a data logger (model CR10X, Campbell Scientific, Logan, Utah). Data were sampled every 10 sec and averaged and stored every minute. From these, the maximum dry bulb temperature was extracted each day the pivot moved for the calculation of T_{dry}.

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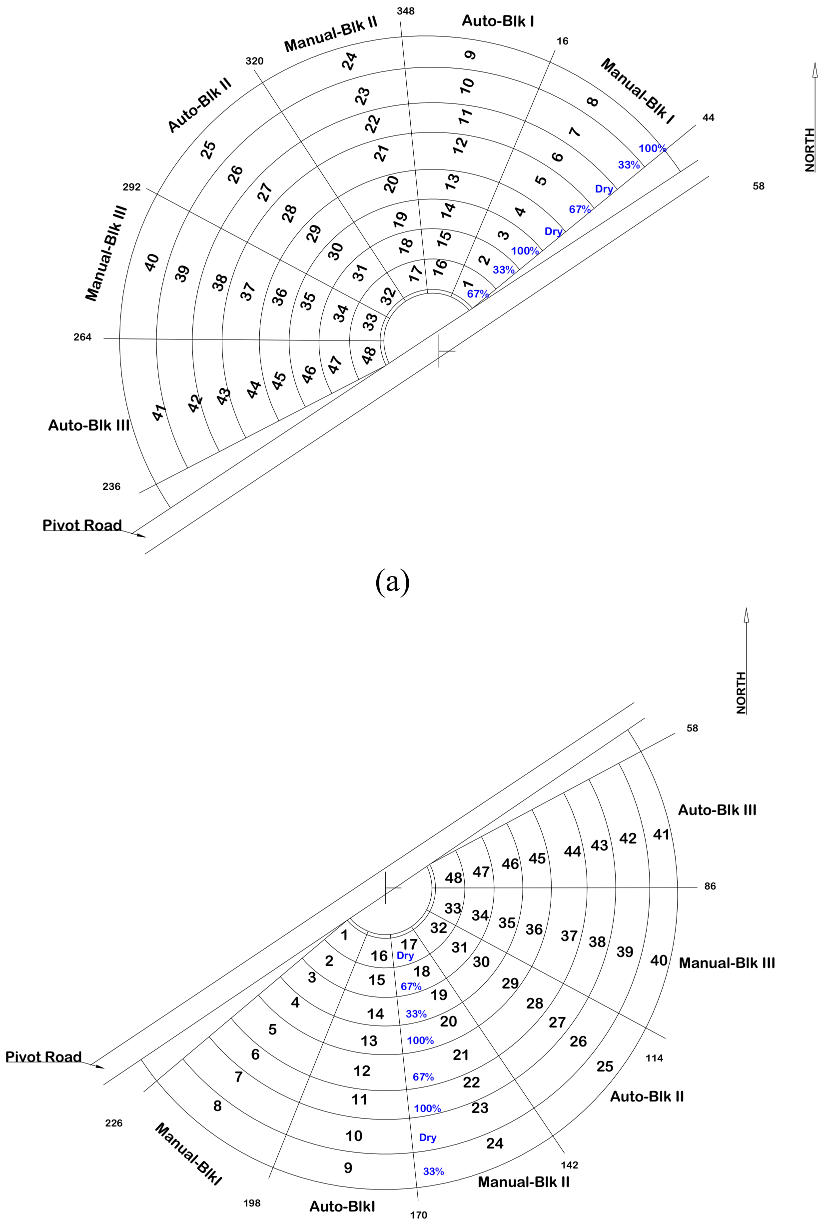
[1] Mention of trade names or commercial products in this paper is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.



(a)

(b)

Figure 1. Experimental layout under the 3-span center pivot irrigation system shown for the (a) 2008 growing season; and (b) the 2007 growing season. Sections were blocked by irrigation method (manual versus automatic) with each block containing two replicates of the four irrigation level treatments, 100%, 67% and 33% and dryland (Dry).

Thermometric Measurements and Image Analysis

Digital images were taken with a thermal infrared camera and processed with corresponding software (model SC2000 and ThermaCAM Researcher Pro 2.8 software, FLIR Systems, Billerica, Mass.) on DOY 223 (Aug. 11), 240 (Aug. 28), 247 (Sept. 4), and 256 (Sept. 13) 2007, and on DOY 213 (July 31) and 261 (Sept. 17), 2008, near solar noon. Concurrent images were taken with an RGB digital camera (model DSC-S85, Sony Electronics, Inc., Oradell, N.J.) mounted alongside the thermal imager to aid in image analysis. Images were taken at a nadir view angle from a hydraulic platform 7.0 m above the ground over treatment plots 1-8 (Fig. 1), covering all four irrigation levels. For each thermometric image acquisition, cardboard crosses covered with aluminum foil were placed in the plant canopy to define the boundaries of interest. The crosses appeared as colder areas in the thermometric images and as bright areas in the RGB images. Canopy temperature for the $\mathrm{CWSI_e}$ was determined by measurement of individual leaves secured to cardboard circles that were also covered with aluminum foil for easy discrimination; the leaves were fully expanded and sunlit. The wet reference was a 27 by 42 cm wet surface constructed from semi-permeable plastic foam blocks covered with white polyester felt resting in a basin filled with deionized water. The foam blocks and felt were submerged to re-wet them at least one min before readings were taken. Capillary action kept the fabric wetted for several minutes. The extracted wet reference temperatures, T_w, were average values of the unshaded areas of the wet reference. The digital photographs were used to improve digital analysis (Fig. 2b). The $\mathrm{CWSI_e}$ was calculated with Eq. [1].

Whole field thermographic scans, taken from the hydraulic lift with the thermal imager, were used to calculate the $CWSI_e$ with Eq. [1] using the canopy temperature, T_c, from the image, the value of T_{dry} determined from maximum air temperature and RH data, and the value of T_{wet} from the wet reference.

Plant measurements

In order to characterize crop water stress, a widely accepted method of assessment was used, measurement of LWP, (Turner, 1988). Ten leaf stem water potential samples were taken from each treatment plot, 1-8, on each sampling day near solar noon. Leaves were excised with a razor blade, wrapped in aluminum foil, and placed in an ice chest until the petiole was inserted into the pressure chamber. All readings were performed within one hour of excision. Leaf water potential measurements were regressed against $\mathrm{CWSI_e}$ values from corresponding treatment plots.

Infrared thermometry and field-wide $\mathrm{CWSI_e}$ determinations

Sixteen infrared thermometer thermocouples (Exergen model IRT/c.5, Watertown, Mass.) with a 5:1 field of view were mounted on masts attached to the center pivot lateral, with two sensors facing into each treatment plot pointed towards the canopy at an oblique angle. One sensor was mounted at the outside edge of each plot and one sensor on the inside edge so that the sensors were aimed nearly towards each other from opposite sides of the plot, thus reducing sun angle effects. IRTs mounted on fixed masts in the fully irrigated treatment plots were used to record the diel variation of canopy temperature for use as the reference temperatures in the temperature scaling method of Peters and Evett (2004). Signals from these sensors were measured and recorded every 10 seconds and averaged and stored for each minute.

Average seasonal CWSI$_e$ values for each of the 48 plots were calculated from data measured on the days the pivot moved using scaled canopy temperatures (T_s) determined for 12:00 pm, CST (Peters and Evett, 2004 and 2008):

$$T_s = T_e + \frac{\left(T_{rmt,t} - T_e\right)\left(T_{ref} - T_e\right)}{T_{ref,t} - T_e} \qquad [2]$$

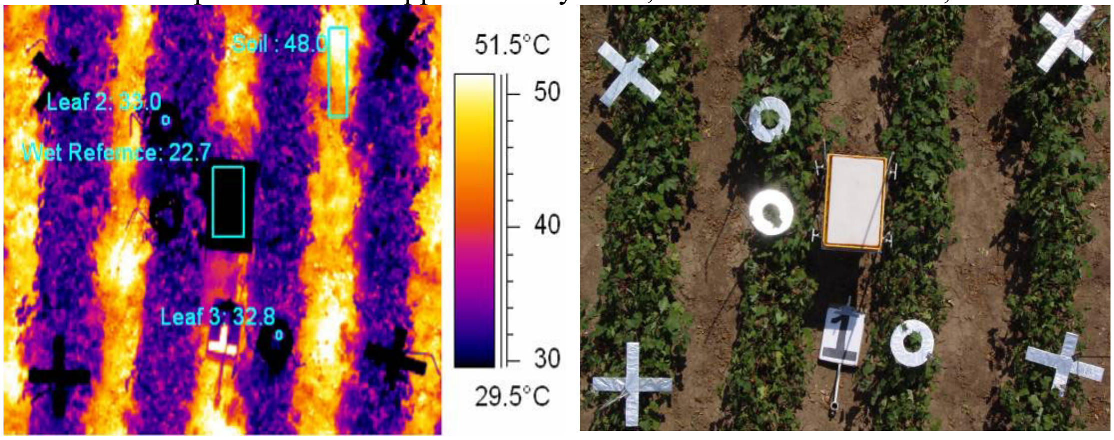
where T_e (°C) was the predawn canopy temperature; T_{ref} (°C) was the reference canopy temperature at the same time interval as T_s (°C) (i.e., 12:00 pm); $T_{rmt,t}$ was the one-time-of-day canopy temperature measurement at the plot (remote location, rmt) at any daylight time t, measured by the IRTs on the pivot arm; and $T_{ref,t}$ (°C) was the measured reference temperature for the time t that the plot (remote) temperature measurement was taken. Mean scaled canopy temperature measurements, T_s, for each treatment plot, were substituted for crop canopy temperature, T_c, in Eq. [1]; the CWSI$_e$ was calculated using T_{dry} = maximum daily dry-bulb temperature (T_{max}) + 5°C, and the wet reference temperature (T_w) estimated using:

$$T_w \approx T_a - \frac{e_s\left(T_a\right) - e_a}{\Delta + \gamma} \qquad [3]$$

where T_a was the air temperature (°C) at 12:00 pm, e_s is saturated vapor pressure (Pa) at T_a, and e_a is actual vapor pressure (Pa), Δ is slope of the saturated vapor pressure versus temperature curve (Pa $°C^{-1}$) evaluated at $(T_a + T_w)/2$, and γ is the psychometric constant (Pa $°C^{-1}$) (Alves et al., 2001).

Results:

Detailed surface temperature data were recorded by thermography as illustrated in Figure 2. Shaded soil temperatures were approximately 42ºC, sunlit soil was > 50ºC, average crop canopy temperature was approximately 32ºC, and the wet reference



(a) (b)

Figure 2. Images taken from 7.0 m above a dryland plot: (a) thermal images of dryland cotton plot, showing average temperature of wet reference, soil, and individual leaves; (b) RBG digital images with wet reference in the center furrow. Photos were taken Sept 13, 2007.

temperature was 22.7°C for this example. The $CWSI_e$ (0.51 for $I_{100\%}$, 0.64 for $I_{67\%}$, 0.78 for $I_{33\%}$, and 1.08 for $I_{0\%}$) derived from temperature data extracted from the whole-field thermal image where furrows are not visible (Fig. 3) provided a qualitative summary comparable to the trend shown in Table 1; the $CWSI_e$ decreases as the irrigation level increases. For accuracy comparable to that obtained from our nadir views, which showed individual leaves, data from whole field images should be digitally processed to normalize the impact of sun angle, percent fraction of vegetation, percent sunlit versus shaded components, and angle of view (Luquet et al., 2003).

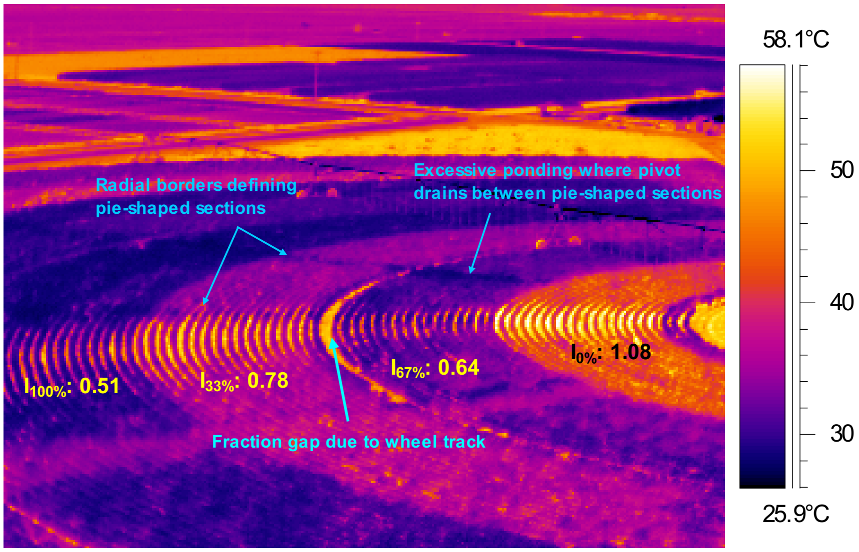


Figure 3. Whole-field image of the cotton field under the 3-span center pivot irrigation system showing the inner four concentric treatment plots ($I_{100\%}$, $I_{33\%}$, $I_{67\%}$, and $I_{0\%}$) and the corresponding values of CWSIe (0.51, 0.78, 0.64, and 1.08, respectively). Thermal image taken at Bushland, TX, on DOY 213 (Jul 31) in 2008.

Table 1. The CWSIe calculated using temperature data extracted from thermal images over individual treatment plots.

2007		Sampling date (DOY)		
Irrigation Treatment	223	240	247	256
0	0.32	0.88	0.85	0.57
33	0.32	0.87	0.77	0.66
67	0.17	0.79	0.56	0.46
100	0.11	0.71	0.48	0.35
2008		Sampling date (DOY)		
Irrigation Treatment	213		261	
0	0.75		0.77	
33	0.56		0.88	
67	0.28		0.81	
100	0.17		0.70	

Simple linear regression of the calculated *$CWSI_e$*, using data extracted from nadir thermal imagery, against leaf water potential measurements demonstrated a strong inverse linear relationship ($r^2 = 0.88$ in 2007; and $r^2 = 0.77$ in 2008). This confirmed that the *$CWSI_e$* was a good indicator of in-field crop water stress (Fig. 4).

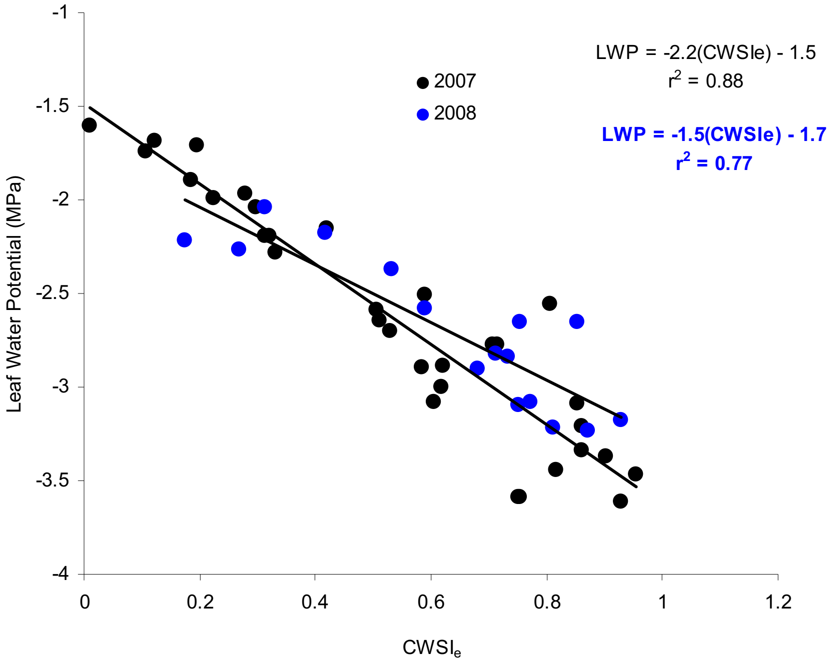
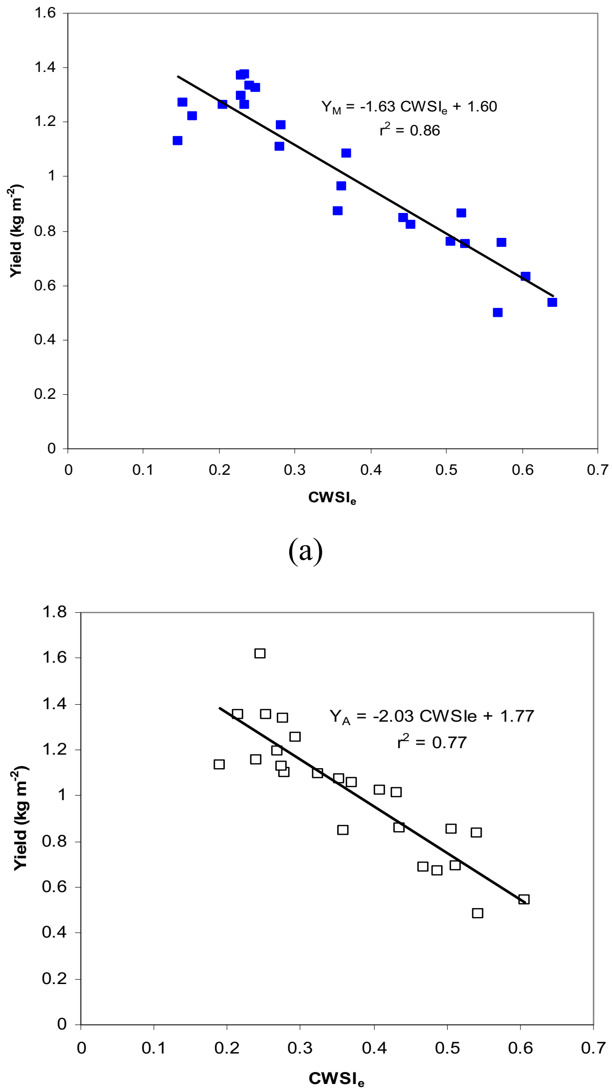


Figure 4. Plot showing the inverse relationship between leaf water potential and the empirical crop water stress index, $CWSI_e$, calculated using an artificial wet reference. Temperature and in situ measurements were made at mid-day during the 2007 and 2008 growing seasons.

These results prompted investigation of the $CWSI_e$ to characterize spatial variability of crop yield for all treatment plots under the center pivot for cotton grown in 2007 and 2008. The plot seasonal mean *$CWSI_e$* explained 86% and 77% of the variation in the manually and automatically irrigated cotton yields, respectively, for the forty-eight treatment plots in 2007 (Fig. 5a and 5b). These results indicated a linear inverse relationship between the *$CWSI_e$* and yields. The linear relationship between lint yield and the seasonal mean *$CWSI_e$* in 2007 was similar to the lint yield relationships reported by Reginato (1983), LY = -1.96(CWSI) + 1.8, and Howell et al. (1984), LY = -1.91(CWSI) + 1.8, for conventional row cotton with 1.0 m spacing, where LY is lint yield and CWSI was calculated using the empirical method by Idso et al. (1981). Similar strongly significant inverse relationships were found by Peters and Evett (2007) between soybean yield, biomass, and total water use versus a seasonal plot mean standardized scaled temperature.

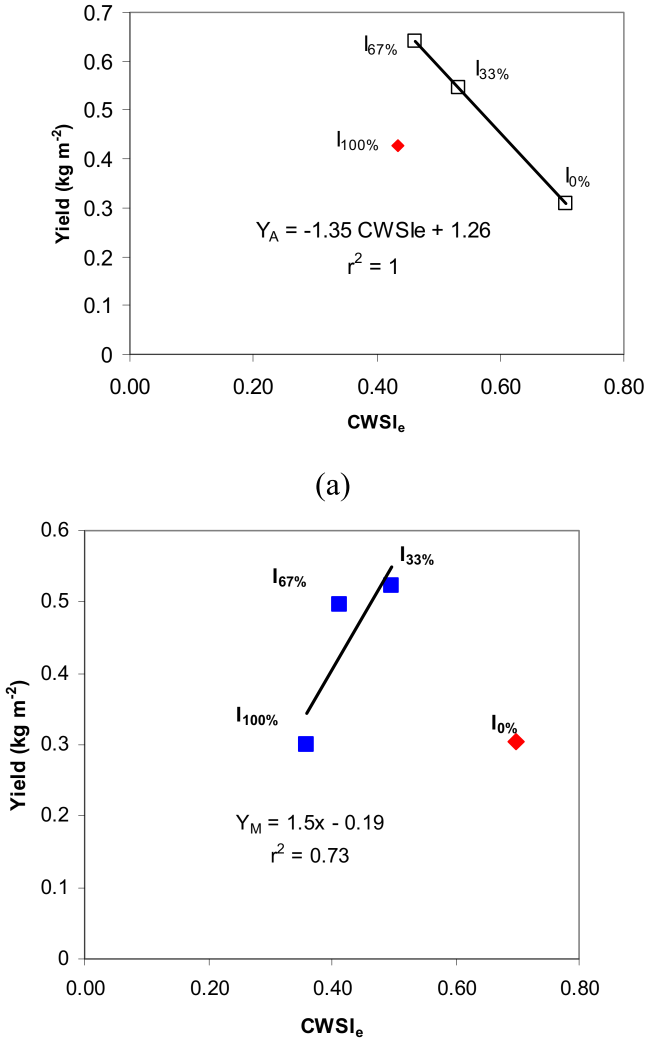


(a)

(b)

Figure 5. The inverse linear correlation between the empirical crop water stress index, *CWSI$_e$*, and yields for both: (a) manually and (b) automatically irrigated plots, 2007.

In 2008, the CWSI$_e$ values for the automatic-deficit irrigated plots were inversely correlated to yields (Fig. 6a) when data from the fully irrigated plots ($I_{100\%}$) were treated as an outlier. This is similar to the trend in 2007. However, for the manually irrigated plots, there existed a strong positive linear correlation between the *CWSI$_e$* and the corresponding manually irrigated yields (Fig. 6b), when the dryland data was treated as an outlier. This relationship indicated that water-stressed cotton produced greater yields than well-irrigated cotton.



(a)

(b)

Figure 6. Cotton yields versus the empirical crop water stress index (CWSIe) for 2008: (a) automatic irrigations; and (b) manual irrigations. Each data point represents the average values from 6 treatment plots.

Mean values for the $CWSI_e$ and yields were used due to variability among individual treatment plots for both the manual and automatic irrigation methods. Overall, cotton production in 2008 was affected by high temperatures and windy conditions at emergence and heavy rainfall in mid August; reducing yields by 70% (data not shown).

Summary and Conclusion

In this study, it was demonstrated that whole-field canopy thermal images provide important qualitative information regarding spatial and temporal crop water status. Nadir thermal images offered detailed canopy temperature data, and an empirical CWSI calculated from thermal images was significantly correlated to concurrent midday leaf water potential measurements. Seasonal plot mean values of $CWSI_e$ were also significantly correlated to crop yield during the 2007 growing season. Because the $CWSI_e$ requires minimal supplementary inputs to provide information on crop water status within a field, it is an inexpensive method of providing feedback to a producer. These early results demonstrated the potential positive impact of infrared thermography and remote canopy temperature sensing on farm management and their end-use as a tool for crop water stress monitoring and yield prediction. Infrared thermography could be used to scan an entire pivot field independent of pivot movement. However, fraction of vegetation, view angle, and cloud cover need to be taken into account. Methods are needed to automate the conversion of field infrared imagery to spatial maps for irrigation scheduling and site specific delivery of water. As thermal imagers become more affordable, automated digital analysis of field imagery taken at different times of the day and converted to useful and easily accessible data could provide decision support information to a producer and a means for improved irrigation and time management. Future studies are needed to evaluate the consistency of the $CWSI_e$'s usefulness during different growing seasons.

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APPLICATION OF MECHANIZED IRRIGATION FOR RICE PRODUCTION

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SUMMARY

Rice, an important staple crop throughout the world, has typically been produced under the same traditional methods for the last 2,000 years or more. The global need to conserve water and various other resources has led to exploring the production of rice under mechanized irrigation. Beginning with a brief history of the development of cultural practices of irrigating rice, this paper will focus on the argument that mechanized irrigation will physiologically and economically work for growing rice. The discussion will be on the general requirements to produce rice with mechanized irrigation such as seed, fertilizer applications, and herbicides. Information will be presented on products available and market acceptance. In closing this work will focus on future issues surrounding the use of mechanized irrigation for rice production and the continued growth and interest in this opportunity.

INTRODUCTION

Rice is one of the most important crops grown around the globe. Produced in over 114 countries, it supplies a major source of nutrition for a large portion of the earth's population (International Rice Research Institute (IRRI), 2008). While some countries previously dependent on rice have become more developed, approximately 750 million people still depend on a stable source of rice from day to day (IRRI, 2006).

Rice has historically been grown in paddies or terraced fields, and now with the evolution of laser leveling, many rice growing areas in the United States have moved to precision leveling or zero grade. It has long been thought that all rice growing areas require ample amounts of water (flood) to maintain the four- to five-inch water level throughout the main growth stages of a rice plant's life cycle. The flood method has the dual purpose of providing weed control and water for plant growth. However due to increasing constraints to available water – both surface and ground changes need to be considered in production techniques for rice (Massey, 2009). Recently, both in the United States and internationally, rice farmers have begun relying heavily on herbicide treatments for weed control in an effort to conserve water by reducing the amount of flood water applied. Other methods are also being implemented to reduce water usage for rice production, which include side inlet and furrow irrigation, as well as reduced flood water levels (Vories, 2006). All of these have one thing in common – they still depend on some form of flood irrigation.

Center pivots would seem a logical choice to irrigate rice as they have successfully irrigated all other grain crops. Center pivot irrigation on rice has been tried by individuals and researchers since the early 1980s. In these attempts, water was saved but the use of center pivots did not meet economic expectations (Deterling, 1983). This was due to a variety of reasons, including weed pressure, wheel tracks, and other management issues (McCauley, 1985). No serious innovations in rice irrigation were implemented until interest was renewed in the late 1990's due to water constraints.

In the early 1990s a Brazilian farmer realized that due to continued water shortages, he needed to make some changes if he wanted to continue to produce rice (Arns, 2007). Working with an agronomist, he tried several alternatives including a traveling gun, reducing the amount of flood water applied, and a small Valley center pivot. Soon it became apparent that the most economically viable solution for his operation was use of the center pivot. A few years later, he had reached a point where he had developed a plan about how to grow rice on his farm under the center pivot. Ever since, he has produced rice profitably under the original center pivot and has expanded his center pivot production area to between 85 and 130 hectares annually. It is this success that has encouraged Valmont to develop a 'formula' for producing rice under mechanized irrigation machines.

DISCUSSION

What, if anything, has changed since the attempts to grow rice with center pivots in the 1980s? Let's discuss the changes in the terms of agronomics, irrigation equipment, and management.

A common problem of center pivot irrigated rice has been weed control; it has been questionable due to the soil being exposed, unlike flooded rice soil, which is typically always covered with water. Through recent trials, however, it has been proven that weed control can be obtained (Bennett, 2009). Obviously every field is site specific and not one chemical regime works everywhere, but based on crop scouting at the United States and Brazilian trials, pre-emergent chemicals and post-emergent herbicides have been applied and have achieved good control. Some advantages of center pivot irrigated fields is the ability to apply water as needed which allows the soil to dry out prior to the use of ground rigs for application, as well as the option to use the center pivot to activate the herbicides.

Another contributor to weed control has been the development of hybrid rice. Just as other agricultural production seeds have rapidly advanced, so has rice been bred for higher yields, disease resistance, and resistance to particular herbicides. The major advancement of hybrid rice not only offers conventional variety characteristics, but also adds an aggressive early season vigor that encourages tillering and canopy development. The crop canopy has been found to be especially important with sprinkler irrigated rice in order to reduce weed pressure throughout the growing season. Hybrid rice has proven to deliver higher yields and improved weed control in flooded rice, and continues this momentum with pivot irrigated rice. Equally important is the disease resistance, particularly Blast, that has been bred into hybrid rice. While hybrid rice seed is not required to sprinkler irrigate rice, it does provide some distinct advantages over varieties.

The next topic for discussion is the consideration of what has changed in irrigation equipment. Center pivots and linear equipment continue to evolve in several areas – controls, drive units, and sprinkler packages. These are important considerations for rice production under center pivots. The controls have improved, allowing for automatic adjustments in application depths which reduce the number of trips the farmer must take to the field. In addition, the incorporation of GPS technology has improved position information. The drive units have changed with the development of reliable and dependable flotation options, such as base beams with three wheels, four wheels, and tracks. These adjustments address one of the key problems that have occurred in the past - center pivots getting stuck. The third important change is improvements in sprinkler packages and hardware; these allow the machine to economically and reliably apply water away from the wheel tracks.

Lastly, improvements in management have changed to meet the unique requirements of producing rice under mechanical move irrigation equipment. It is understood that irrigating rice is not the same as irrigating other crops, and a unique approach needs to be taken. The exceptional characteristics of the rice plant require different thought about when to irrigate and the required application depth. Production trials continue to determine optimum irrigation depths and scheduling. Another management concept is the advantage of using the center pivot or linear machine to apply fertilizers, which improves efficiency while minimizing application costs (Stevens, 2008).

CONCLUSIONS

Recent results with rice production under center pivots have been successful for specific individuals. Different producers have their own reasons for using mechanized irrigation. For the Arnses in Brazil, conserving 50% or more of their water typically used in their flooded fields and the ability to still produce a good rice yield are the drivers. Other growers want a viable alternative crop that has the potential for positive economic return on fields that are not suitable for traditional rice production methods. Using center pivots and linears reduces the amount of land leveling required, thereby minimizing the amount of water needed for production and easier rotation to other crops.

Work needs to continue to better understand the actual water needs of rice and the irrigation requirements by growth stage, what type of flotation options are needed for which soil type, chemigation and fertigation and seeding rates to name a few to reach the point where growers can reliably anticipate achieving their economic goals when using mechanized irrigation for rice production.

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Water Conservation's Role in California Water Transfers

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This paper describes various irrigation district water transfer projects. Water transfers have been of many types, including agriculture to agriculture, agriculture to urban, and agriculture to environment. In each case that will be described, the unique circumstances of each district will be described. Typical actions include developing a water balance to determine if "wet water" truly exists for conservation, then identifying the sources of that wet water. Subsequent actions include developing designs that will conserve the water, achieving board approval, and constructing and implementing the conservation measures.

California is "water challenged" because the water sources are often at opposite ends of the state from the large water users. Figure 1 clearly shows the geographical rainfall discrepancies.

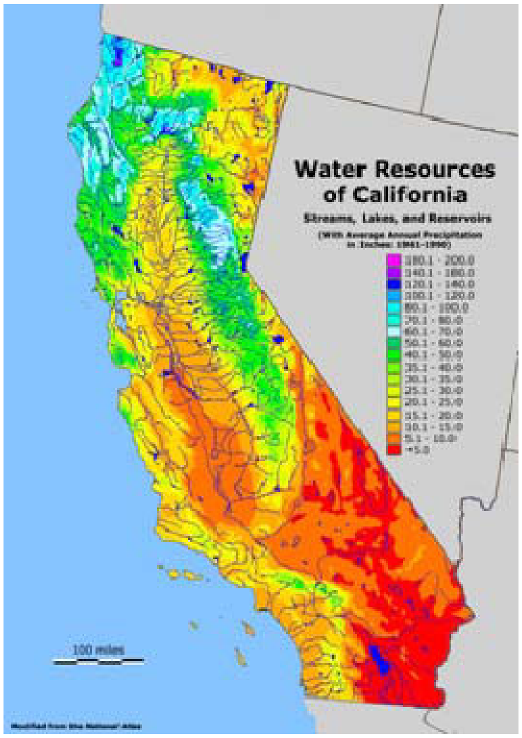


Figure 1. Geographical rainfall discrepancies of California.

On the other hand, California is fortunate because it has a system of canals that links the southern area of the state (with large urban areas such as the Los Angeles basin and San Diego) with the northern areas of the state and with the Colorado River. Therefore, assuming that there are not flow capacity restrictions (physical or regulatory), it is often possible to move water from one area of the state to another, through legal agreements called "water transfers". While the majority of transfers are fairly local in nature (between farmers within a single irrigation district, or between neighboring irrigation districts), others involve movement of water for many hundreds of miles.

Figure 2. California's Major Water Projects. Courtesy Calif. DWR.

The California Water Code treats water transfers as a "reasonable and beneficial use" of water that is held with a water right. Because most of the water resources in the state are controlled by irrigation districts or some type of quasi-public agency (such as a county water agency), most of the water transfers are from one agency to another. Individual farmers within an irrigation district do not generally have the right to sell their water (whether surface water or groundwater or "in-lieu of" water) as individuals. When an irrigation district decides to transfer water outside or within its boundaries, it may give financial incentives to individual farmers to release all or a portion of their individual water allocations. There are some cases in which individual farms, falling outside of irrigation district boundaries but with abundant surface water rights, have transferred water.

There must be some type of "win-win" arrangement between the two parties, and there must be a physical means of transferring the water. The benefits of water transfers are not always unanimously agreed upon within the members of the agency that is doing the selling. Roadside signs that argue against water transfers are common in California's northern Sacramento Valley, which is often seen as a potential water source by water users to the south. Lawsuits to prevent water transfers are common in the Imperial Valley. Regardless of location, both imagined and real fears can surface regarding eventual loss of water rights, groundwater overdraft, loss of local control, the price received for the water, protection against future environmental lawsuits, loss of income due to projects such as fallowing, arrogance of water agency staff, and just about any other issue.

The "win" for the purchaser is quite simple – water is obtained. In the summer of 2009, some farmers with permanent crops in the San Joaquin Valley were willing to pay as much as $500 per acre-foot or more for water. The alternative was dead trees or vines. In many agricultural areas there is no alternative to surface water supplies; groundwater is not available. The concept of individual farmers with no water being able to conserve their way out of a drought was, of course, unrealistic.

Municipalities must weigh the cost of purchasing water against the costs of alternative supplies such as from desalinization, recycling of treated wastewater, or eliminating discharges into the ocean. Municipalities near the ocean can truly conserve water with simple practices such as installing low flush toilets and low flow showerheads – assuming their wastewater is presently discharged into the ocean.

The agricultural suppliers of water for a water transfer have a variety of motivations. Three examples will be provided here:

Case 1: Imperial Irrigation District. The Imperial Irrigation District (IID) supplies Colorado River water to about 500,000 acres of irrigated land in the Imperial Valley in southern California, at the border with Mexico. Its only drainage outlet is the Salton Sea, which is a land-locked salt lake that has increasing salinity levels. Any water that enters the Salton Sea is truly lost for future use in agriculture or in municipalities.

IID has commissioned several water balance studies over the years – spending millions of dollars on the studies themselves, plus the collection of the data that are required for study inputs. IID has a good quantification of inflows, rain (almost none), lateral inflows, and outflows. It also has good information on the source of the outflows to the Salton Sea. Specifically, it knows the volumes that originate as canal seepage, farm surface runoff, farm tile outflows, and canal spills (main and lateral). Over the years, IID has invested heavily in various conservation measures to minimize outflows to the Sea, some of which have been successful and others of which have been less successful.

IID has several motivations to conserve water. On one hand, it is almost always the subject of some court ruling, mandate by the California Water Resources Control Board, requirement by the US Bureau of Reclamation, or orders from some other group or agency that demands water conservation. Furthermore, the Public Trust Doctrine in California implies that if a water right holder does not make reasonable and beneficial use of its water, then it will lose that portion of water that is used unreasonably.

By finding an urban purchaser of conserved water, IID can satisfy the external demands for water conservation yet simultaneously receive the funds needed to implement the conservation efforts – which are not trivial. This is an extremely important point – if IID simply fallows land to conserve water, the economy will be negatively impacted. If, on the other hand, IID can invest in infrastructure improvements that truly conserve water both on-farm and in its delivery system (now and in the future), then it can safely function with less imported water. Agriculture will remain strong, the farmers will not need to pay for the improvements that are demanded by external entities, and IID will position itself as a conservation leader that is helping to solve water shortages in urban areas. Furthermore, under current California law, IID retains ownership of the transferred water.

In the late 1980's, IID entered into an historic water transfer agreement with Metropolitan Water District of Southern California (MWD). MWD paid in advance for water conservation measures such as tailwater return systems, canal lining, and canal automation. Approximately 108,000 acre-feet were conserved and transferred; IID received about $100.5 million (1988 dollars), all of which was spent for the purposes of planning, executing, and verifying water conservation measures. The average (1988 $) cost per acre-foot conserved was $127.

More recently, IID entered into a new agreement with San Diego County Water Authority. Under this agreement, IID must first conserve the water before SDCWA pays. The agreement is to transfer about 300,000 acre-feet per year by 2026, at an annual cost of about $270/acre-foot (including administration, loan payback, annual on-farm expenses, maintenance, construction, etc.) Approximately two-thirds of the conserved water is envisioned to come from on-farm savings; the remainder will come from seepage collection from canals and from canal spill reduction.

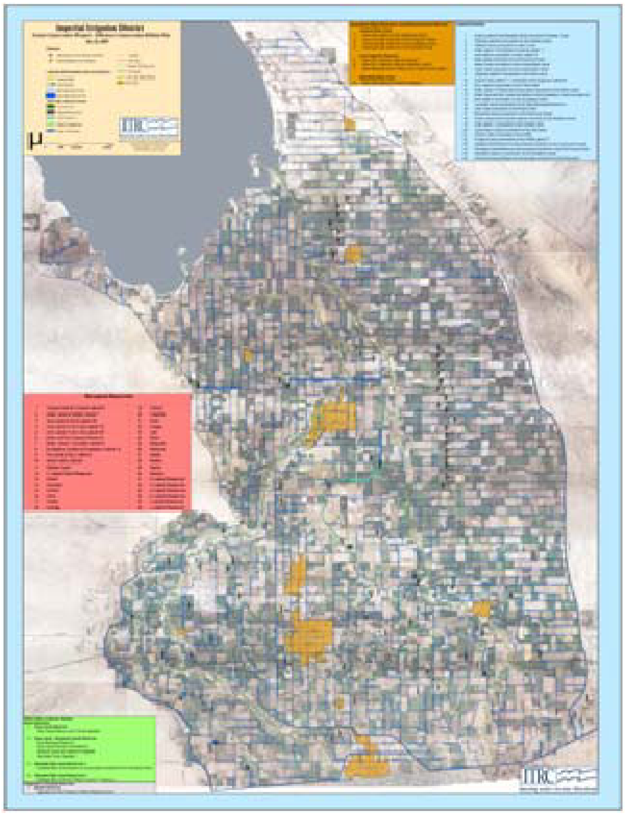


Figure 3. Early plan for spill reduction in IID.

The IID/SDCWA water transfer agreement was part of a complex process called the Quantification Settlement Agreement (http://www.bbklaw.com/news-press-168.html) that has involved numerous federal and state agencies along with lawsuits against IID by farmers, Imperial County, and others. The execution of the agreement is targeted to begin in 2010. Land fallowing is not part of the program.

A key point is that conserved water in IID can be transferred to the Los Angeles and San Diego areas via the Colorado River aqueduct. That canal/pipeline system begins near Lake Havasu on the Colorado River.

Case 2: Palo Verde Irrigation District (PVID). PVID (near Blythe, California) is another large irrigation district on the Colorado River, but it is in an entirely different hydrologic situation than IID. PVID has downstream water users – the Yuma area irrigation districts, IID, and Coachella Valley Water District. Canal spill and tailwater runoff from within PVID is recycled (albeit with a slightly lower water quality) back into the Colorado River and is therefore available for usage by downstream users. As opposed to IID, reducing spill and tailwater runoff in PVID will not conserve water. Instead, the only way to truly conserve water is to reduce evapotranspiration (ET).

In PVID, farmers have been receptive to water transfer programs that require them to fallow land (i.e., not irrigate the land). This is a politically unacceptable option in Imperial Valley, which has a high unemployment rate.

PVID has had several land fallowing programs in the past, including an on-going 35-year program. Land fallowing can be relatively simple to administer and verify. If land is not irrigated, there must be a water savings. In terms of true water conservation, however, actual benefits depend on what crop has been fallowed. For example, a short term winter crop of wheat will not consume the same ET as a full year crop of alfalfa. Land fallowing programs in some districts (e.g., in the Klamath Basin) incorporate a detailed study of historical cropping patterns on fields, and allocate a water conservation volume depending upon that history.

This year PVID entered into a short-term program with MWD. Every farmer irrigating land in the Palo Verde Valley with Priority 1 Colorado River water supplies was eligible to enroll up to 15% of that land. The enrolled land must be fallowed for one continuous year, commencing between April and August 2009. MWD paid farmers $1,665 for each acre enrolled, with an additional payment of $35/acre to PVID. Farmers are responsible for minimizing weed growth and avoiding wind erosion.

<u>Case 3: Glenn-Colusa Irrigation District (GCID)</u>. GCID is located in the Sacramento Valley of California – upstream of the California Delta. This location is important, because the people and entities that need the water are south of the Delta, and there are serious limitations to pumping from the Delta. Water must be pumped from the Delta into the California Aqueduct or Delta-Mendota Canal in order to reach southern users. Various environmental court rulings have restricted pumping flow rates, with the goal of recovering endangered fish species in the Delta.

Figure 4. Location of GCID

In general, there are strong anti-transfer sentiments in some communities in northern California. Specifically, people are often concerned that a substitution of groundwater for surface water, by farmers, will deplete the groundwater aquifers.

In 2009, GCID's board of directors approved a voluntary short-term agreement between GCID and the California Dept. of Water Resources, to transfer up to 6,843 acre-feet of water to the "2009 Drought Water Bank". There are three items of interest:

- The flow rate into GCID is in the 2000 CFS range, which means that the water transfer represents about 3 days of water diversion for GCID. This is not a huge percentage.
- GCID did not allow groundwater substitution; only idled land was eligible.
- The state of California facilitated the deal with its "Drought Water Bank".

California's 2009 Drought Water Bank

The California Dept. of Water Resources initiated emergency dry year water purchasing programs in the past, such as in the early 1990's, and in 2001-2004. In 2009, DWR purchased water from willing sellers upstream of the Sacramento-San Joaquin Delta. The goal was to move that water through the Delta by gravity, and then pump into the California Aqueduct or the Delta-Mendota Canal. The policies that DWR adopted included (from DWR's website http://www.water.ca.gov/drought/docs/2009water_bank.pdf):

- Local water needs are considered as a priority before water is transferred out of the region.
- Transfers will be made without injuring other legal water users and without unreasonably affecting fish, wildlife, or other instream beneficial uses.
- Transfers will be made without unreasonably affecting the overall economy or the environment of the county from which the water is transferred.
- No more than 20% of the cropland in any county may be idled due to the 2009 Drought Water Bank, unless additional evaluations are conducted related to both the economic and environmental impacts.
- Transfer water will be those water supplies that would not have been available in the Delta absent the transfer.
- Water will be allocated in accordance with priority of need, with health and safety considerations paramount.
- Transfers and related actions need to be in compliance with federal and state environmental laws as applicable and local ordinances consistent with State law.
- Transfers through State Water Project (SWP) facilities for use in a SWP contractor's service area will be conveyed under existing SWP long-term water supply contracts and through SWP Contractors.
- Transfers involving water supplies made available pursuant to the Federal Central Valley Project (CVP) water service and/or water right settlement contracts must comply with the terms and conditions of the existing CVP contract.
- Transfer recipients are expected to have and implement an adopted water management plan including conservation measures designed to result in a minimum of 20% overall savings.

A key point for the irrigation districts was that DWR provided California Environmental Quality Act (CEQA) and Endangered Species Act (ESA) compliances.

DWR allowed willing sellers to make water available in four main ways:

- Reservoir releases above normal operations
- Groundwater substitution
- Cropland idling (fallowing)
- Crop substitution

Other Transfers

ITRC is involved with a number of other water conservation and water transfer efforts by districts. In some cases, districts see the water transfers as an opportunity to be proactive, and to upgrade their distribution systems with someone else paying the bill.

Some districts see water transfers as a means of reducing water rates inside their own boundaries. Some crops have low returns this year, and a water transfer is seen as a viable means of keeping some farming operations afloat.

The biggest concerns by districts that transfer water seem to be:

1. Will the water right eventually be lost? Those districts that believe this are investing in better infrastructure so that they can survive with less water. The districts that are simply paying their farmers are not investing in the future, and may have serious problems later.
2. Is groundwater substitution healthy? California has a groundwater overdraft of more than 2 million acre-feet per year. So in general, groundwater substitution is sounding less and less attractive. Farmers are beginning to see increased salinity in groundwater supplies, and the water tables are dropping – raising pumping bills. Some (including the author) are concerned that some farmers are building up salt in their root zones for short-term profits.
3. Will fallowing land hurt the local economy? Third party impacts can be large.

The Future

California uses more water than it has. There is a need for all users to be more efficient – farmers, urban areas, and environmental users. At first glance this will sound like a pro-agriculture, biased statement – but it is true that there is very little conservation potential in California's irrigated agriculture. The reason is simple: there is tremendous under-irrigation at present, and much of the losses are recirculated in the hydrologic basins. The big exceptions are the Imperial Valley and Coachella Valley (which drain into the Salton Sea) and some limited areas near the Coast.

Another exception is irrigated lands that overlie salty groundwater. It is somewhat coincidental that these lands, generally found on the western side of the San Joaquin Valley, suffer from under-irrigation and expensive water. Therefore, the amount of deep percolation is "relatively" small in those areas.

So where will irrigated agriculture go in California? Here are some predictions:

1. More irrigated land will be abandoned. Large areas of Westlands Water District, and the complete Broadview WD, have been permanently idled. This abandonment will increase – and will be focused in areas that have some combination of a shortage of water, overdrafted groundwater basins, and serious drainage problems (the tile drainage flows into rivers is restricted because of high salt loads or especially toxic salts such as selenium or boron). Perhaps an additional 300,000 – 500,000 acres of such land will be abandoned over the next 20 years.
2. Yields/acre will increase. This is already happening. Large acreages of processing tomatoes have yields greater than 70 tons/acre (as opposed to 40 tons being high 10 years ago). Almond yields are regularly passing 4000 lb/acre (compared to 2000 as a high number 20 years ago). This is due to better irrigation design and management, plus improved varieties, pest management, and overall agronomic practices.
3. The California Delta problem will largely be resolved with new conveyance systems that allow efficient transportation of water through and around the Delta – providing both environmental protection and more reliable water transfers from north to south.

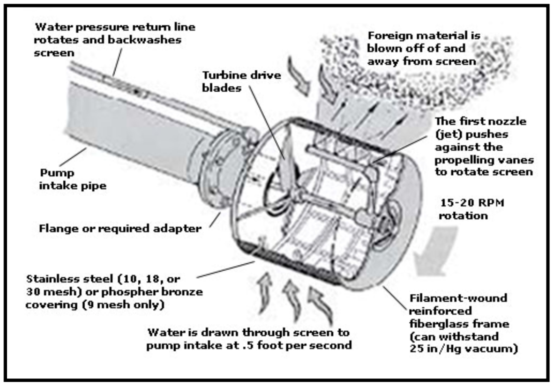
4. More agricultural land will be urbanized. In general, urbanization into ranchettes results in less evapotranspiration per acre because the ranchettes are poorly managed and weedy after a few years.
5. Cities will become more efficient, with new restrictions on landscape irrigation and more recycling of water instead of dumping sewage into the ocean. Desalination will accelerate. This will stabilize the urban requirements for water.

The bottom line with more efficient environmental usage of water, less agriculture, and more efficient urban usage will be a stabilization of acreage for irrigated agriculture – but with higher overall yields than we currently have. Much of the art of irrigation will disappear, and be replaced with transferrable knowledge associated with science and engineering.

Sand vs. Sand Filters:
A Case For Reduced Backwashing

Sand media filtration is a respected and proven methodology for removing algae, fine silt and organic matter from pumped water for drip irrigation and micro-spray irrigation systems. By their nature, sand filters not only effectively remove these fine solids, but also (not-so-effectively) remove larger particle matter, too. Solids such as +200 mesh sand and stringy organic matter are even more easily removed from the water stream via a sand filter. Unfortunately, such particle matter/debris are not-so-easily removed from a sand filter. Instead, consider the logic of applying two or more filter techniques to solve the overall contaminant problem, rather than depending on one filter to do all the work … which often results in overwhelming a filter or causing it to fail.

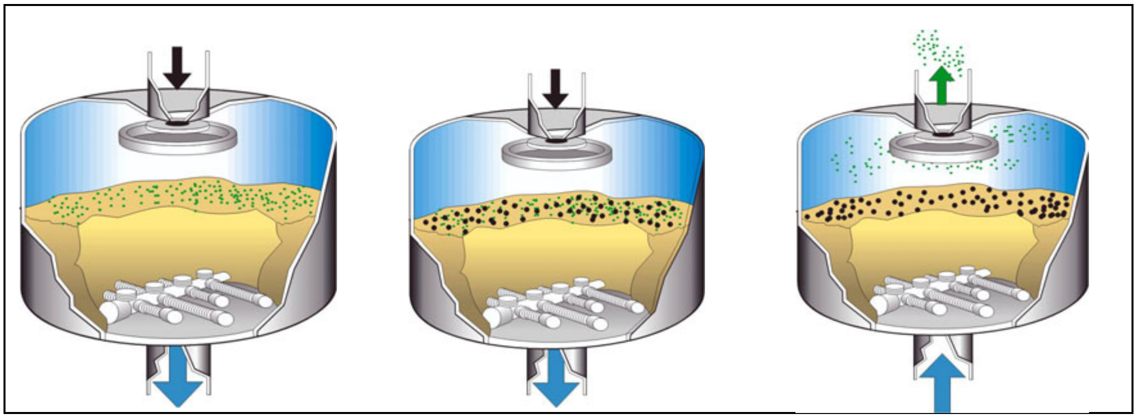
Stringy organic material can build-up quickly on a sand media bed surface, causing high pressure loss in a short period of time. Problematic also is the occurrence of such material being able to foul the dispersion plates at the inlet to a sand filter, when such debris interweaves or gets impacted onto the plates, vanes and/or coarse screening of a sand filter's dispersion devices. Pre-filtering at the water source, before the debris gets to the pump, is an intelligent alternative, relying upon alternative technology designed for the removal of such debris. Self-cleaning pump intake screens, for example, can keep such larger debris from not only fouling a sand filter, but also damaging a pump.



How a Self-Cleaning Intake Screen Works

More subtle, but more prevalent, is the fouling of a sand media filter by allowing or relying on a sand filter to remove larger sand particle matter. This problem almost always begins with the common indicator of a rapid-to-continuous pressure loss. What happens after that can be even more detrimental to the performance and ability of the sand filter to function as desired.

Excessive backwashing. Designed to respond to a pressure differential, a sand filter will read high pressure loss and trigger a backwashing cycle to rid the media bed of the unwanted debris. However, if the unwanted debris includes heavy sand particles, backwashing may not relieve the full measure of pressure loss caused by the intrusive sand. Backwashing, by design, is set to allow a reversing flow of water to remove debris trapped on the media bed's surface layer (typically the top 2-3 inches) without blowing any substantial amount of the media sand itself via the backwash process. The result, if heavy sand is present, is a residual leftover of intrusive sand that prevents the sand filter from cleansing itself to a desirable low pressure differential. Backwashing in such scenarios becomes more and more repetitive at shorter operating cycles as the intrusive sand builds-up a new layer on the sand media bed surface, triggering backwash cycles more frequently. At times, if left unchecked, the backwashing can become nearly continuous as the sand filter responds (as programmed by the automatic controller) to the pressure differential setting of the system. Significant water can be lost in such instances.



Fine sand & organics (far left) are easily captured by the sand media. Larger/heavier particle matter (middle) also are easily trapped by the sand media. Backwashing, however, has limited influence (far right) on the heavier/larger particle matter, causing residual build-up and greater pressure loss issues.

EXAMPLE: A three-tank media filter system, operating at 650 gpm with water drawn from a sandy river water source, was backwashing 860 gallons of water per backwash cycle. This system had gotten to the point that it was backwashing at a frequency of every 15 minutes, resulting in a loss of 3,440 gallons of water every hour. A sand separator was installed to pre-filter the water and remove the heavier sand particles, resulting in a reduced backwashing rate of only every four hours (the equivalent of only 215 gallons of water per hour). The savings, a 94% reduction in water loss, amounted to a volume of one acre-foot of water every week. And that doesn't include the savings in reduced pumping costs, just to provide that water for backwashing the filter system.

Ineffective backwashing. In the example above, the filter system was not able to rid itself of the cause of excessive pressure loss. In another common scenario, the sand filter can quickly become so fouled with fine sand (50-250 mesh size) that backwashing cannot produce the flow necessary to clean itself. Each tank quickly builds-up a formidable and deep layer of fine sand and, when the filter system switches to its backwash mode, the water cannot effectively pass through any of the filter tanks, providing inadequate flow & pressure to properly backwash the fine sand from the media bed's surface. Unchecked, the fine sand remains on the media bed surface of each tank and more fine sand is pumped into the filter system, adding further build-up until backwashing becomes not only highly repetitive, but likely near continuous.

EXAMPLE: A six-tank media filter system is operating at 1,200 gpm, drawing from a water well with both sand and silt problems. With pump start-up being a particularly vulnerable time to draw sand from the well, the media bed of each tank quickly became loaded with sand & silt. Backwashing immediately became continuous and the system had to be either shutdown or bypassed in order to deliver water to the field. Manual cleaning of the sand bed surface provided no relief, as each start-up delivered more problematic sand & silt to rapidly trigger a backwash cycle, which could not be performed effectively, due to the increasing build-up across all the filter tanks. A sand separator was installed to protect the sand filter from the coarse-to-fine sand particles, allowing only the much finer silt to pass into the sand filter system. With a much lighter and less voluminous layer of build-up, the sand filters were able to deliver the backwash water volume and pressure necessary to effectively flush the lighter debris from the filter tanks and restore the system to a much lower operating pressure loss differential.

Migration of organics deep into the media sand. This problem can come from either over-pumping beyond the limit of the sand filter's recommended flow range, and/or from a combination of very fine organics and a media sand that is too coarse for the contaminant to be removed. The result is that the fine organics are driven deep into the media sand, clogging the interspacial open areas of the media sand deeper in the tanks than the recommended top 2-3 inches of the media bed. This clogging not only restricts the free flow of water through the filter system, but also makes it extremely difficult to backwash the more deeply-imbedded debris from the filter tanks in the typically allotted time frame for backwashing (usually 90-180 seconds). Build-up increases until backwashing becomes overly frequent. This condition can be difficult to detect, as backwashing appears to flow from dirty-to-clean in the typical backwash duration, but it is the debris that resides deeper in the filter tanks that is causing the greater amount of pressure loss. Even "super-flushing" has its limitations, ultimately resulting in the need to replace the sand … and it typically should be replaced with a finer media sand to trap the contaminants in the upper layer of the sand media bed. At times, adding more filter tanks and reducing the flow per tank, can also improve the operating conditions, especially if the water has a greater than average load of organic debris.

Pre-Filtering Tips

When pre-filtering can help reduce backwashing, there are three important guidelines to understand. And, it's important to understand the capabilities and limitations of a filter to contribute to reduced pressure loss.

Selective efficiency. Don't select a filter that can equally remove the same particle matter as the sand filter. The goal of pre-filtration is to remove debris that the prime filter (the sand filter) cannot remove and cannot handle. Fine screens or discs will demand greater servicing routines and may offset the benefits of pre-filtration. Also, organics can become problematic to filters better suited for the removal of sand & silt. A sand separator, which removes only sand and not organics, allows the lighter contaminants to pass into the sand filter, which is better suited for that kind of contaminant removal.

Load management. Consider the water source and the range of contaminants in the water source. Reduce the volume and the burden on the sand media bed. The pre-filter need not address all of a given contaminant, but rather the greater volume or greater sizes only.

Pressure loss. Filters that trap debris and add pressure loss to a water system can limit the overall system's efficiency and ability to perform. With most drip/micro systems already operating at low pressures, adding pre-filters that add more pressure loss may be problematic. Better yet, consider pre-filters that offer a predictable and/or fixed pressure loss. Sand separators, for example, operate at a pressure loss dictated only by flow rate, not by contaminant build-up; that pressure loss could be built into the system's design without concern for fluctuations.

Reduced backwashing not only improves the operating efficiency of a sand media filter system, but also reduces servicing & maintenance routines and reduces significant water loss. All of these issues translate to reduced operating costs and improved environmental conditions. With the understanding that drip & micro-spray systems save water and money, it makes even greater sense that minimizing a sand filter's backwashing routines will save even more water and money.

Quantifying Effective Rain in Landscape Irrigation Water Management

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Abstract

Climatologically based control systems measure evapotranspiration, yet often fail to quantify effective rainfall. Many parts of the country receive more rain than ET. For control systems to effectively manage landscape irrigation, both ET_c and effective rainfall need to be quantified.

Effective rain is the amount of rain which is useful to the plant. Several factors must be considered to quantify effective rain. Rain that falls faster than the soil can absorb may run off. Soil moisture holding capacity is limited by soil type and root depth. Soil moisture holding capacity and current moisture content limit the amount of useful rain.

This report will identify each of the factors that limit the effectiveness of rain and will offer a method to quantify rain that will be useful to plants. By implementing this process, water managers can determine when irrigation should resume after it rains to more effectively eliminate wasteful over-watering.

Key Words

Effective Rain, Saturation Allowance, Water Management, Rain, Irrigation, Moisture Balance, Run-off, Saturation, Allowed Depletion, Check Book Method, Root Depth, Root Zone Capacity, Soil Type, ET, Evapotranspiration, Smart Controller, Climate, Root Zone Storage, Field Capacity, Permanent Wilt Point, Rain Gauge, Irrigation Amount, Efficiency, Maximum Hourly Rainfall Rate, Available Water.

Introduction

The landscape irrigation industry is responding to the need to use water efficiently on two fronts; improving distribution uniformity, and providing self-adjusting controllers. The most common “smart” controllers are climate-based, which utilize weather sensors to calculate evapotranspiration (ET); the loss of water to the atmosphere by evaporation from the soil and plants. If a Smart Controller knows how much water has evaporated from the landscape, then the controller knows how much to water needs to be replaced.

Many Smart controllers measure ET and then use a rain shut-off device. Smart controllers can be smarter by measuring both ET and rain. With both measurements, a Smart controller will not irrigate during rainfall and it will know when irrigation should resume after it rains. This is where rain shut-off devices fall short; too often watering resumes sooner than needed. The result is that plants get too much water and roots remain shallow, so water is wasted and plant health is compromised.

Much of the country receives more rain than ET, so irrigation supplements rain. Rain changes more dramatically than ET. During the growing season ET may range from 0.05″ to 0.40″ per day. A rain storm can easily deliver twice that amount, but is all rain effective?

There is good science to quantify effective rain to avoid wasteful overwatering. A close look at the process also exposes steps that can be taken to increase the effectiveness of rainfall.

Concept

The soil must be seen as a reservoir. Rain and irrigation fill the soil reservoir. Reservoirs have a capacity. The capacity of the soil reservoir is based on soil type and rooting depth. The amount of water in the reservoir changes; moisture is depleted from the soil by evaporation. Rain and irrigation refill it. When the reservoir is overfilled, water runs off or soaks below the roots. Effective Rain is rain that is useful to plants.

For decades soil moisture has been estimated using the Checkbook Method of irrigation scheduling. ET “withdraws” from the “account”; rain and irrigation make “deposits. By implementing the Checkbook method with hourly resolution, rainfall can be better accounted for. A Smart control system will know to stop irrigation when it rains and will also know when irrigation should resume.

To quantify effective rain there are four areas that need to be considered:

- Measuring Rain
- Percolation vs. Run-off
- Root Zone Storage
- Moisture Balance

Measuring Rain

A common method to measure rainfall is a “tipping bucket” gauge. Rain is funneled into a bucket or cup that tips when filled to a calibrated level, typically 0.01″ or 1mm. As the bucket tips, a magnet attached to the tipping mechanism actuates a switch. The momentary switch closure is counted and logged by circuitry in a datalogger or control system. Logging resolution typically ranges from 1 to 60 minutes.

Percolation vs. Run-off

Rain will be absorbed by the soil as fast as gravity, pore space and capillary action will allow. Soil type, compaction, and organic content all have a bearing on percolation rates. Rain that falls faster than the soil can absorb will accumulate on the surface of the soil. The slope of the surface will result in the water running away from the plant making it no longer useful to the plant.

Percolation rates and precipitation rates are typically expressed in inches per hour. By comparing the percolation rate to the rainfall rate, the amount of water that can soak into the soil is quantified. Rain in excess of percolation rates can be characterized as run-off.

Soil composition and compaction affect percolation rates. The following table offers accepted ranges of soil moisture intake rates:

Percolation Rate	
Soil Type	**Inches Per Hour**
Sand/Fine Sand	1.50-3.00
Loamy Sand	1.00-2.00
Sandy Loam	.80-1.20
Loam	.40-.60
Silty Loam	.25-.40
Silt	.30-.50
Sandy Clay Loam	.10-.30
Clay Loam	.07-.25
Silty Clay Loam	.05-.12
Sandy Clay	.08-.20
Silty Clay	.05-.15
Clay	.05-.10

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Organic content and compaction are the primary variables that influence the actual percolation rate. An onsite test or visual inspection can help refine the site's percolation rate.

Root Zone Storage

Once rain is absorbed by the soil, plant roots can access this water. An extended rainstorm may result in water percolating below the root zone or running off the surface. In either case the rain is no longer useful to the plant.

The soil is like a reservoir or tank that holds water. Soil reservoir capacity is limited by pore space in the soil and root depth.

Consider this example. Compare the soil reservoir to a glass of water. How much water can be drunk from the glass through a straw? It depends on how much ice is in the glass; ice represents soil particles. Particle size, shape and compaction affect the capacity of the remaining pore space. It also depends on how far the straw goes in the glass; a straw represents the roots. The reservoir capacity will increase as the roots go deeper.

Both the capacity and current soil moisture content must be considered to quantify how much rain will be held in the root zone. Before going any further, a review of the terms used to describe soil moisture content may be helpful.

> **Saturation** – All open pore space in the soil is filled with water. Gravity drains water from a saturated condition. Depending on soil type, drainage typically stops within 2-3 days after a saturating rain storm.

Field Capacity – The soil is considered to be at Field Capacity once the moisture held in soil after excess rain or irrigation stops draining. Visualize water draining from a sponge when pulled from a bucket, when the draining stops, there is still water held in the sponge. A significant amount of water is held in the soil by capillary force.

Permanent Wilt Point – The point where the plant can no longer draw water from the dried soil, the plant will either die or go into a dormant state.

Soil moisture holding capacities vary based on soil type, compaction and organic content. Available Water is defined as the amount of water in the soil between “Field Capacity” and Permanent Wilt Point. Soil charts express holding capacity as Available Water in inches of water per inch or per foot of soil. The following chart shows Available Water in inches per inch of soil.

Available Water	
Soil Type	**Inch / Inch ***
Sand	.03--.07
Loamy Sand	.06--.08
Sandy Loam	.11--.13
Loam	.16--.18
Silty Loam	.19--.21
Silt	.16--.18
Sandy Clay Loam	.14--.16
Clay Loam	.19--.21
Silty Clay Loam	.19--.21
Sandy Clay	.15--.17
Silty Clay	.15--.17
Clay	.14--.16

* National Engineering Handbook, Part 652 Irrigation Guide

To determine the Root Zone Storage capacity, a core sample should be pulled to examine the length of the roots. When doing this inspection, remember roots are very fragile and very small, give the roots the benefit of the doubt, roots are often deeper than perceived with a simple visual inspection.

Root Zone Storage capacity can be estimated by taking Available Water (inch/inch) x Root Depth. For example if we assume the mid-range of the Available Water in a Sandy Clay Loam Soil (0.15” per inch) and turf with a 6” root depth the Root Zone Storage is 0.90”. (6 x 0.15 = 0.90)

In addition to the storage identified by using the Available Water table, there is short term “storage” when the soil becomes saturated. Once a storm is over, water in a saturated condition will begin to drain and evaporate until it reaches Field Capacity.

Drainage may take several days. During this time this water is available to the plants and will evaporate from the soil.

The following chart demonstrates the amount of additional water that can saturate a soil beyond Field Capacity.

Mosisture as % of Volume		
Soil Type	**Field Capcity**	**Saturation**
Sand/Fine Sand	14%	37%
Loamy Sand	15%	38%
Sandy Loam	20%	42%
Loam	27%	46%
Silty Loam	28%	46%
Silt	30%	44%
Sandy Clay Loam	29%	44%
Clay Loam	32%	50%
Silty Clay Loam	35%	52%
Sandy Clay	32%	50%
Silty Clay	43%	54%
Clay	45%	54%

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Soil conditions and root depth can be used to quantify a Saturation Allowance or the amount of extra water the soil can hold beyond Field Capacity. The concept of a Saturation Allowance is not commonly recognized. There is no disagreement regarding the difference between Field Capacity and Saturation. The above sited USDA table provides a means to quantity this value. This value can be estimated based on the Available Water at Field Capacity and Moisture as a % of Volume. The following table combines Moisture as a percent of Volume data with Available Water at Field Capacity to provide an estimate of Maximum Saturation Allowance.

Soil Type	Average Available Water at Field Capacity - Inch / Inch	Mosisture as % of Volume (PER USDA)		Total Water at Saturation - Inch / Inch	Maximum Saturation Allowance	
		Field Capcity	Saturation		Inch / Inch	Percent of Available Water
Sand	0.05	14%	37%	0.13	0.08	164%
Loamy Sand	0.07	15%	38%	0.18	0.11	153%
Sandy Loam	0.11	20%	42%	0.23	0.12	110%
Loam	0.16	27%	46%	0.27	0.11	70%
Silty Loam	0.2	28%	46%	0.33	0.13	64%
Silt	0.2	30%	44%	0.29	0.09	47%
Sandy Clay Loam	0.15	29%	44%	0.23	0.08	52%
Clay Loam	0.16	32%	50%	0.25	0.09	56%
Silty Clay Loam	0.18	35%	52%	0.27	0.09	49%
Sandy Clay	0.12	32%	50%	0.19	0.07	56%
Silty Clay	0.15	43%	54%	0.19	0.04	26%
Clay	0.14	45%	54%	0.17	0.03	20%

However, this table does NOT consider the time it takes for water to drain from a saturated condition. I have not found any research that provides a means to definitively quantity a practical means to quantify a Saturation Allowance. Research has shown drainage time ranges from 1 to 3 days depending on soil conditions. In recognizing this condition exists, for the last several years I have been advising water managers to apply a Saturation Allowance when implementing a Moisture Balance. I have recommended and used 25% of Available Water as a means to estimate a Saturation Allowance. Limiting the value to 25% of Available Water provides a generous allowance for drainage time. Water managers may change the Saturation Allowance after observing site conditions after it rains. Feedback from projects with automated water management, using a 25% Saturation Allowance, has been very positive. All indications are this value has resulted in effectively delaying watering after it rains.

There should be no question there is a difference in soil moisture content between Field Capacity and Saturation. Water held in this state is available to the plant and can evaporate. Current methodology suggests any moisture beyond Field Capacity should be characterized as run-off. This approach results in premature resumption of irrigation. Implementing a Saturation Allowance in the Checkbook method of irrigation management will increase the effectiveness of rain.

Moisture Balance

The storm is over, the sun comes out and the landscape begins to dry because of evaporation and transpiration. The question is; when should irrigation resume after it rains? - Once soil moisture is depleted by ET to an allowable level.

The goal of an effective water manager is to irrigate once the soil dries out to a manageable level, and return it to Field Capacity; not irrigate to keep the soil saturated. When a soil is saturated, oxygen is replaced with water; all the pore space is filled. Plant roots need air; too much water forces roots to remain shallow in order to breathe.

The irrigation industry teaches the principle of Allowed Depletion. The soil should dry out to an allowable level between irrigation cycles. Using the Allowed Depletion method provides an accurate process to determine irrigation frequency and when irrigation should resume after it rains.

The most effective way to implement the principle of Allowed Depletion is by using the Checkbook Method of Irrigation Scheduling. This method has been used for decades as a means of determining irrigation frequency and amount. The process compares ET to a “withdrawal” from the “Checking Account” and irrigation and rain as a “deposit”. Once the balance reaches Allowed Depletion irrigation is needed.

Traditionally the Checkbook is implemented with daily calculations. ASCE recommends hourly ET calculations. When the moisture balance is calculated hourly, using

Checkbook method, Effective Rain can be easily accounted for. The math is simple, each hour ET is subtracted from the "balance," effective rain and irrigation is added. The Checkbook must be calculated respecting site specific limits. Site conditions such as soil type and root depth need to be used to define the limits of the "account" or soil reservoir. There are a number of variables that affect these limits.

Maximum Hourly Rain – Soil conditions affect percolation rates. Soil tables are a beginning point to determine the maximum amount of rain the soil can absorb.

Root Zone Capacity - Soil type and root depth give us enough information to estimate the Root Zone Capacity, also referred to as Available Water. (See Available Water chart).

Allowed Depletion - Horticulturists have indicated the best management practice is to deplete soil moisture to an allowed depletion level of 30% to 60% of Available Water. A 50% Managed Allowed Depletion is a well accepted standard. In other words, soil moisture should be depleted to half of the available water before irrigation should occur.

Optimum Irrigation Amount - The purpose of irrigation is to refill the soil reservoir to Field Capacity. In a perfect world the optimum irrigation amount is equal to the amount of Allowed Depletion. The actual irrigation amount may vary based on when watering occurs and the availability of water.

Moisture Balance Reference – The Checkbook needs to be referenced to the soil moisture content. Using a value of zero as equal to the point of Allowed Depletion provides a logical reference. Once soil moisture is depleted to "0" then it is time to irrigate. Using a reference of zero may imply the soil is bone dry, which is not true; it does suggest irrigation is needed. The soil offers its own "overdraft protection," if zero is equal to the point of Allowed Depletion there is still additional moisture in the soil. Remember, when using a 50% Managed Allowed Depletion only half of the Available Water has been depleted.

Accepting a value of 0 as equal to a depleted soil moisture level means that when the soil has reach Field Capacity the moisture balance is equal to Allowed Depletion.

Moisture Balance Limits – The Checkbook needs maximum and minimum limits referenced to soil moisture conditions.

A minimum limit to a moisture balance is Permanent Wilt Point which equates to 0 minus Allowed Depletion.

The maximum limit of a soil moisture balance is Saturation. Once the soil is saturated, water will accumulate on the surface and may run off. A Saturation Allowance provides a water manager the means to account for additional water that will soak in and saturate the soil. A maximum limit to the moisture level would be equal to the Allowed Depletion value plus a Saturation Allowance.

With capacities and constraints set within the Checkbook and moisture balance limits defined, data can now be applied to a mathematical model of soil moisture content.

There are three inputs to the Checkbook; rain and irrigation make “deposits,” and “withdrawals” come as a result of ET. ET is a measurement of the amount of water lost to the atmosphere as a result of evaporation and transpiration. A measurement of climate conditions including, solar radiation, temperature, wind and humidity are used to calculate a reference ET value, referred to as ET_o. The ET formula is based on a reference crop. By multiplying a crop coefficient (K_c) to ET_o, a more exact estimate of plant evaporation may be applied to the Checkbook ($ET_o \times K_c = ET_c$).

In summary these are the formulas that have been described:

Root Zone Capacity (RZC)

RZC = AW x RD

Where:

AW = Available water in inches per inch of soil

RD = Root Zone Depth in Inches

Allowed Depletion (AD)

AD = RZC x MAD%

Where:

RZC = Root Zone Capacity (inches)

MAD% = Management Allowed Depletion Percent (decimal value)

Maximum Moisture Balance (MAX)

MAX = AD + SA

Where:

AD = Allowed Depletion

SA = Saturation Allowance

Minimum Moisture Balance (MIN)

MIN = 0 - (RZC x (1 - MAD%))

Where:

RZC = Root Zone Capacity (inches)

MAD% = Management Allowed Depletion Percent (decimal value)

The following is an example of an implementation of the Checkbook method of modeling soil moisture with a set of variables:

Variables

Soil Type	Sandy Clay Loam
Available Water in/in	0.11
Root Depth - Inches	8.00
Managed Allowed Depletion	50%
Saturation Allowance	0.22
Maximum Hourly Rain	0.35

Resulting Limits

Root Zone Capactity	0.88
Allowed Depletion	0.44
Optimum Irrigation Amount	0.44
Moisture Balance Limit	0.66

Date	ETc	Total Rain	Rain Limited by Max Hourly	Effective Rain	Irrigation	Moisture Balance
7/1/2006 3:00:00 AM	0.005	0.00	0.00	0.00	0.00	0.01
7/1/2006 4:00:00 AM	0.005	0.00	0.00	0.00	0.44	0.44
7/1/2006 5:00:00 AM	0.000	0.00	0.00	0.00	0.00	0.44
7/1/2006 6:00:00 AM	0.000	0.00	0.00	0.00	0.00	0.44
7/1/2006 7:00:00 AM	0.001	0.00	0.00	0.00	0.00	0.44
7/1/2006 8:00:00 AM	0.003	0.00	0.00	0.00	0.00	0.44
7/1/2006 9:00:00 AM	0.005	0.00	0.00	0.00	0.00	0.43
7/1/2006 10:00:00 AM	0.006	0.00	0.00	0.00	0.00	0.42
7/1/2006 11:00:00 AM	0.013	0.00	0.00	0.00	0.00	0.41
7/1/2006 12:00:00 PM	0.016	0.00	0.00	0.00	0.00	0.40
7/1/2006 1:00:00 PM	0.008	0.00	0.00	0.00	0.00	0.39
7/1/2006 2:00:00 PM	0.002	0.00	0.00	0.00	0.00	0.39
7/1/2006 3:00:00 PM	0.002	0.00	0.00	0.00	0.00	0.38
7/1/2006 4:00:00 PM	0.002	0.02	0.02	0.02	0.00	0.40
7/1/2006 5:00:00 PM	0.003	0.03	0.03	0.03	0.00	0.43
7/1/2006 6:00:00 PM	0.003	0.41	0.35	0.23	0.00	0.66
7/1/2006 7:00:00 PM	0.001	0.01	0.01	0.00	0.00	0.66
7/1/2006 8:00:00 PM	0.001	0.00	0.00	0.00	0.00	0.66
7/1/2006 9:00:00 PM	0.000	0.00	0.00	0.00	0.00	0.66
		0.47		0.29		
				61%		

There are several lessons that can be learned from this example. Notice irrigation occurred at 4:00 in the morning. Soil moisture was returned to Field Capacity. Rain began later in the afternoon. Two factors limited the amount of Effective Rain. 1) The rainfall rate at 6:00 PM exceeded the soil intake rate, so only 0.35″ of rain was accepted. 2) Also note that the soil reservoir was nearly full. The rain at 6:00 PM saturated the soil. The total rainfall was 0.47″ but Effective Rain was only 0.29″ or 61%.

Examples

The next four pages are reports calculated by implementing the Checkbook method of irrigation scheduling with hourly data for a 30 day period. The data is actual recorded data from the locations noted. Changes were made to site variables to demonstrate the effects. To make it easier to see the results, the calculations have been compiled into a daily summary. A graph of the hourly Moisture Balance is included to provide another method of examining the results.

Rain storms can come with different intensities and durations. Example 1 provides an example of a wet cycle followed by a dry period. ET rates during the rain are much lower because of cloud cover, higher humidity and cooler temperatures. Notice in example 1 irrigation was delayed for nearly a week after the bulk of the storm passed. During that time it was cool, overcast and very light rain fell on several days.

Example 2 shows what can happen with much heavier rains. The percent of Effective Rain is much less than in Example 1. In this mid-summer example it rained 14 days. There were only 5 days when irrigation was needed during the entire month; the Checkbook Method correctly identified the appropriate 5 days.

Look closely at Example 3 and 4, the only one change was made to the setup. Example 3 has a 3” root depth, which limits Allowed Depletion and the Saturation Allowance. Example 4 has a 6” root depth, which results in an increased Allowed Depletion and Saturation Allowance. Notice how the watering frequency and Effective Rain are affected by this one change.

Example 1 Aurora, CO

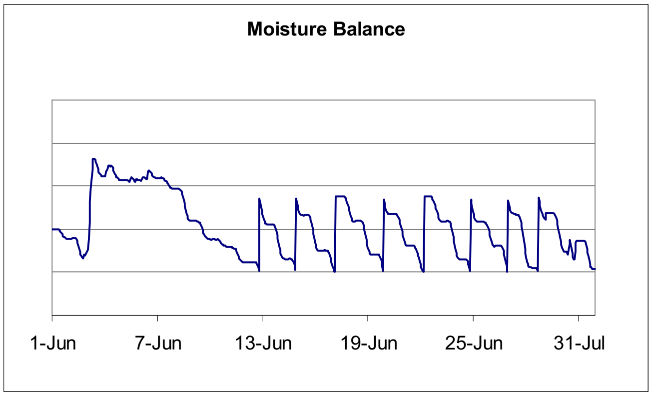
Rain Fall Efficiency: 99%

Variables

Soil Type	Sandy Clay Loam
Available Water in/in	0.11
Root Depth - Inches	8.00
Managed Allowed Depletion	50%
Saturation Allowance	0.22
Maximum Hourly Rain	0.35

Resulting Limits

Root Zone Capactity	0.88
Allowed Depletion	0.44
Optimum Irrigation Amount	0.44
Moisture Balance Limit	0.66



Moisture Balance

Date	ET	Total Rain	Effective Rain	Irrigation	Moisture Balance
6/1/2008	0.06	0.00	0.00	0.00	0.19
6/2/2008	0.12	0.04	0.04	0.00	0.11
6/3/2008	0.12	0.58	0.57	0.00	0.56
6/4/2008	0.09	0.07	0.07	0.00	0.54
6/5/2008	0.06	0.06	0.06	0.00	0.53
6/6/2008	0.07	0.08	0.08	0.00	0.55
6/7/2008	0.07	0.01	0.01	0.00	0.48
6/8/2008	0.19	0.00	0.00	0.00	0.30
6/9/2008	0.11	0.00	0.00	0.00	0.19
6/10/2008	0.06	0.02	0.02	0.00	0.15
6/11/2008	0.10	0.01	0.01	0.00	0.06
6/12/2008	0.14	0.00	0.00	0.44	0.36
6/13/2008	0.21	0.00	0.00	0.00	0.15
6/14/2008	0.19	0.00	0.00	0.44	0.40
6/15/2008	0.21	0.00	0.00	0.00	0.20
6/16/2008	0.15	0.00	0.00	0.00	0.05
6/17/2008	0.13	0.00	0.00	0.44	0.36
6/18/2008	0.20	0.00	0.00	0.00	0.16
6/19/2008	0.21	0.00	0.00	0.44	0.40
6/20/2008	0.16	0.00	0.00	0.00	0.24
6/21/2008	0.17	0.00	0.00	0.00	0.07
6/22/2008	0.16	0.00	0.00	0.44	0.35
6/23/2008	0.19	0.00	0.00	0.00	0.16
6/24/2008	0.22	0.00	0.00	0.44	0.37
6/25/2008	0.16	0.00	0.00	0.00	0.22
6/26/2008	0.21	0.00	0.00	0.00	0.00
6/27/2008	0.30	0.00	0.00	0.44	0.14
6/28/2008	0.24	0.00	0.00	0.44	0.34
6/29/2008	0.18	0.04	0.04	0.00	0.20
6/30/2008	0.28	0.26	0.26	0.00	0.18
Total	4.74	1.17	1.16	3.52	
			99%	8 Water Days	

Example 2   Houston, TX

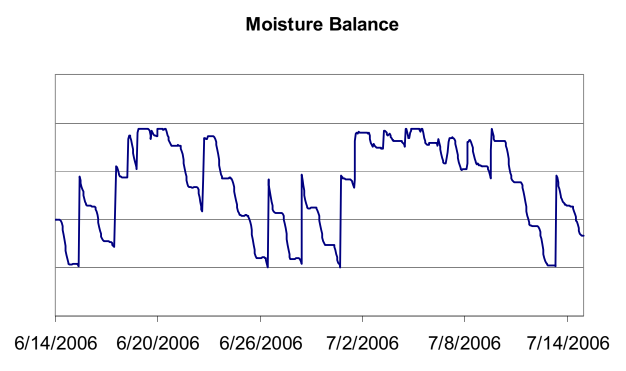
Rain Fall Efficiency: 36%

Variables

Soil Type	Clay Loam
Available Water in/in	0.16
Root Depth - Inches	6.00
Managed Allowed Depletion	50%
Saturation Allowance	0.24
Maximum Hourly Rain	0.20

Resulting Limits

Root Zone Capactity	0.96
Allowed Depletion	0.48
Optimum Irrigation Amount	0.48
Moisture Balance Limit	0.72



Moisture Balance

Date	ET	Total Rain	Effective Rain	Irrigation	Moisture Balance
6/14/2006	0.23	0.00	0.00	0.00	0.02
6/15/2006	0.18	0.00	0.00	0.48	0.32
6/16/2006	0.18	0.00	0.00	0.00	0.14
6/17/2006	0.09	1.13	0.42	0.00	0.47
6/18/2006	0.18	0.48	0.43	0.00	0.72
6/19/2006	0.10	0.94	0.06	0.00	0.68
6/20/2006	0.11	0.40	0.06	0.00	0.63
6/21/2006	0.22	0.00	0.00	0.00	0.42
6/22/2006	0.14	0.60	0.40	0.00	0.68
6/23/2006	0.22	0.00	0.00	0.00	0.46
6/24/2006	0.19	0.00	0.00	0.00	0.27
6/25/2006	0.22	0.00	0.00	0.00	0.05
6/26/2006	0.25	0.00	0.00	0.48	0.28
6/27/2006	0.24	0.00	0.00	0.00	0.05
6/28/2006	0.22	0.00	0.00	0.48	0.31
6/29/2006	0.19	0.00	0.00	0.00	0.12
6/30/2006	0.14	0.00	0.00	0.48	0.46
7/1/2006	0.07	0.55	0.31	0.00	0.70
7/2/2006	0.11	0.03	0.03	0.00	0.62
7/3/2006	0.08	0.11	0.11	0.00	0.65
7/4/2006	0.09	0.59	0.16	0.00	0.72
7/5/2006	0.11	1.34	0.04	0.00	0.65
7/6/2006	0.15	0.07	0.07	0.00	0.57
7/7/2006	0.16	0.10	0.10	0.00	0.51
7/8/2006	0.14	0.16	0.16	0.00	0.53
7/9/2006	0.14	0.68	0.26	0.00	0.66
7/10/2006	0.21	0.00	0.00	0.00	0.44
7/11/2006	0.23	0.00	0.00	0.00	0.22
7/12/2006	0.20	0.00	0.00	0.00	0.01
7/13/2006	0.17	0.00	0.00	0.48	0.32
7/14/2006	0.16	0.00	0.00	0.00	0.16
Total	5.09	7.18	2.61	2.40	
			36%	5	Water Days

Example 3 Logan, UT

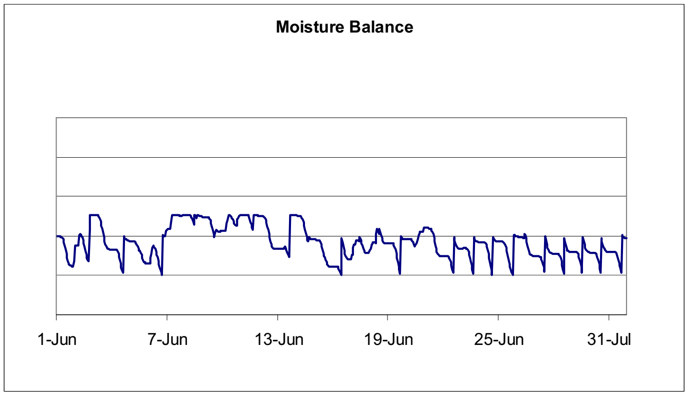
Rain Fall Efficiency: 45%

Variables

Soil Type	Silty Clay Loam
Available Water in/in	0.17
Root Depth - Inches	3.00
Managed Allowed Depletion	50%
Saturation Allowance	0.13
Maximum Hourly Rain	0.35

Resulting Limits

Root Zone Capactity	0.51
Allowed Depletion	0.26
Optimum Irrigation Amount	0.26
Moisture Balance Limit	0.38



Moisture Balance

Date	ET	Total Rain	Effective Rain	Irrigation	Moisture Balance
6/1/2009	0.19	0.03	0.03	0.00	0.09
6/2/2009	0.18	1.37	0.47	0.00	0.38
6/3/2009	0.22	0.00	0.00	0.00	0.16
6/4/2009	0.20	0.00	0.00	0.26	0.22
6/5/2009	0.15	0.01	0.01	0.00	0.08
6/6/2009	0.19	0.14	0.14	0.26	0.28
6/7/2009	0.06	0.97	0.16	0.00	0.38
6/8/2009	0.13	0.55	0.12	0.00	0.37
6/9/2009	0.15	0.06	0.06	0.00	0.28
6/10/2009	0.08	0.38	0.18	0.00	0.38
6/11/2009	0.11	0.39	0.11	0.00	0.38
6/12/2009	0.21	0.00	0.00	0.00	0.17
6/13/2009	0.09	0.33	0.30	0.00	0.38
6/14/2009	0.18	0.03	0.03	0.00	0.23
6/15/2009	0.17	0.00	0.00	0.00	0.06
6/16/2009	0.21	0.00	0.00	0.26	0.10
6/17/2009	0.13	0.17	0.17	0.00	0.15
6/18/2009	0.14	0.20	0.20	0.00	0.20
6/19/2009	0.23	0.00	0.00	0.26	0.23
6/20/2009	0.07	0.15	0.15	0.00	0.30
6/21/2009	0.18	0.00	0.00	0.00	0.12
6/22/2009	0.20	0.00	0.00	0.26	0.17
6/23/2009	0.22	0.00	0.00	0.26	0.21
6/24/2009	0.25	0.00	0.00	0.26	0.21
6/25/2009	0.22	0.00	0.00	0.26	0.25
6/26/2009	0.17	0.04	0.04	0.00	0.12
6/27/2009	0.24	0.00	0.00	0.26	0.14
6/28/2009	0.24	0.00	0.00	0.26	0.15
6/29/2009	0.26	0.00	0.00	0.26	0.14
6/30/2009	0.25	0.00	0.00	0.26	0.15
7/31/2009	0.17	0.00	0.00	0.26	0.24
Total	5.49	4.82	2.17	3.32	
			45%	13 Water Days	

Example 4 Logan, UT

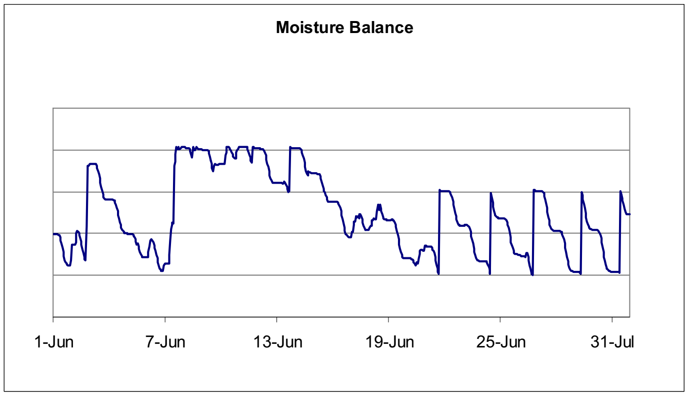
Rain Fall Efficiency: 63%

Variables

Soil Type	Silty Clay Loam
Available Water in/in	0.17
Root Depth - Inches	6.00
Managed Allowed Depletion	50%
Saturation Allowance	0.26
Maximum Hourly Rain	0.35

Resulting Limits

Root Zone Capactity	1.02
Allowed Depletion	0.51
Optimum Irrigation Amount	0.51
Moisture Balance Limit	0.77



Moisture Balance

Date	ET	Total Rain	Effective Rain	Irrigation	Moisture Balance
6/1/2009	0.19	0.03	0.03	0.00	0.09
6/2/2009	0.18	1.37	0.76	0.00	0.67
6/3/2009	0.22	0.00	0.00	0.00	0.45
6/4/2009	0.20	0.00	0.00	0.00	0.25
6/5/2009	0.15	0.01	0.01	0.00	0.11
6/6/2009	0.19	0.14	0.14	0.00	0.06
6/7/2009	0.06	0.97	0.77	0.00	0.77
6/8/2009	0.13	0.55	0.12	0.00	0.75
6/9/2009	0.15	0.06	0.06	0.00	0.67
6/10/2009	0.08	0.38	0.18	0.00	0.77
6/11/2009	0.11	0.39	0.11	0.00	0.76
6/12/2009	0.21	0.00	0.00	0.00	0.55
6/13/2009	0.09	0.33	0.30	0.00	0.76
6/14/2009	0.18	0.03	0.03	0.00	0.61
6/15/2009	0.17	0.00	0.00	0.00	0.44
6/16/2009	0.21	0.00	0.00	0.00	0.23
6/17/2009	0.13	0.17	0.17	0.00	0.27
6/18/2009	0.14	0.20	0.20	0.00	0.33
6/19/2009	0.23	0.00	0.00	0.00	0.10
6/20/2009	0.07	0.15	0.15	0.00	0.18
6/21/2009	0.18	0.00	0.00	0.51	0.50
6/22/2009	0.20	0.00	0.00	0.00	0.30
6/23/2009	0.22	0.00	0.00	0.00	0.08
6/24/2009	0.25	0.00	0.00	0.51	0.34
6/25/2009	0.22	0.00	0.00	0.00	0.12
6/26/2009	0.17	0.04	0.04	0.51	0.51
6/27/2009	0.24	0.00	0.00	0.00	0.26
6/28/2009	0.24	0.00	0.00	0.00	0.02
6/29/2009	0.26	0.00	0.00	0.51	0.27
6/30/2009	0.25	0.00	0.00	0.00	0.02
7/31/2009	0.17	0.00	0.00	0.51	0.37
Total	5.49	4.82	3.06	2.55	
			63%	5 Water Days	

Observations

There are a number of lessons that can be learned and conclusions drawn from these four examples.

Rain fall amounts are sporadic; in these examples daily rainfall amounts range from 0 to 1.37″. During the same period ET ranges from only 0.06″ to 0.26″. Rain can be a higher variable and needs to be properly accounted for to effectively manage irrigation. What matters to the plant is the actual water that is available to it.

A simple percentage applied to total rainfall is not an accurate method for quantifying Effective Rain. Example 1 and 2 clearly demonstrate the percent of Effective Rain varies. Rainfall rate, soil conditions, root zone capacity, and soil moisture content when it begins to rain all affect how much rain is useful to plants.

The single most important factor that affects how much rain becomes effective is the Root Zone Storage Capacity. This is apparent when comparing example 3 and 4. Both examples use the same ET and rain. The only change to example 4 was root depth. Changing the root depth increased the capacity of the root zone storage; 23% less water was needed for irrigation because the soil could hold more rain.

A close look at the moisture balance prior to a rain storm reveals another factor that affects the amount of effective rain. When the moisture balance is near allowed depletion then there is more room in the soil to hold the water. The opposite is also true, if irrigation had just occurred prior to the rain; the soil reservoir is already full, not leaving much room for rain.

In looking at the data from these examples most rainfall rates did not exceed soil intake rates. But, occasionally a heavy storm did occur, demonstrating the importance of ignoring rainfall values that exceed soil intake rates.

Increasing Effective Rain

Rain must have a place to go. If the soil reservoir was recently filled by irrigation or rain, there may not be much room left in the reservoir to hold the rain. Soil moisture content when a storm begins limits the amount of Effective Rain. If rain is in the forecast, turning irrigation off will leave room in the soil reservoir for a coming storm.

Irrigation and horticultural management practices can promote a deeper root system which increases the soil reservoir capacity. More rain is effective because it can be stored in the root zone. Deep, less frequent watering will promote deeper roots. Better soil preparation and aeration can also increase root depth.

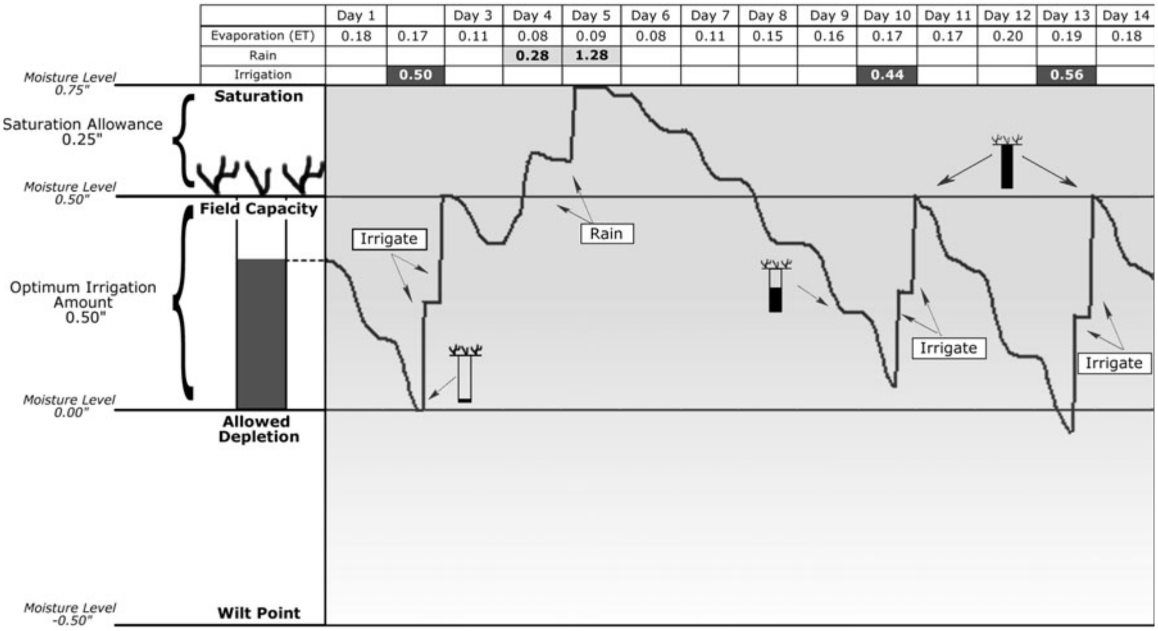
Rain shut-off devices do not measure rain. After a heavy rain, a shut-off device allows irrigation to resume sooner than needed. Automated control systems should measure rain and maintain a soil moisture balance using the Checkbook method of irrigation management.

When tight soil conditions limit soil intake rates, adding mulch, cultivating and aerating the soil or adding soil amendments can loosen the soil to improve permeability.

Summary

This example demonstrates the affects of implementing the presented principles. Site specific soil reservoir capacities were defined. Soil moisture is modeled using the Checkbook Method. Two days of rain resulted in a delay in irrigation for six days.

Irrigation Moisture Balance



	Day 1		Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
Evaporation (ET)	0.18	0.17	0.11	0.08	0.09	0.08	0.11	0.15	0.16	0.17	0.17	0.20	0.19	0.18
Rain				0.28	1.28									
Irrigation		0.50								0.44			0.56	

Hourly ET$_c$ and rainfall measurements implemented in the Checkbook method of irrigation management and the application of a Saturation Allowance provide the means to improve automated water management. Rain is more accurately accounted for, which reduces the amount of water needed for irrigation.

Conclusions

- In a majority of the country measuring rain is as important as measuring ET.
- Effective rain cannot be determined by taking a percentage of total rain.
- Effective rain can be quantified by measuring rain and implementing an hourly moisture balance model using the Checkbook method of irrigation management.
- By quantifying Effective Rain, a control system can delay irrigation after it rains to avoid unnecessary watering.
- With proper management rainfall effectiveness can be improved.
- Roots need a balance of both air and water. When watering is delayed until soil moisture reach allowed depletion, air is drawn into the root zone. Landscapes health improves when soil moisture is managed properly.
- Water and money can be saved with improved irrigation control that considers Effective Rain to reduce wasteful overwatering.

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Modeling pecan growth and fertilization under nitrogen and water stress

Presented at the 2009 Irrigation Show, Innovations in Irrigation Conference, December 2-4 in Henry B. Gonzalez Convention Center, San Antonio, TX

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Abstract

Rising fertilizer costs and diminishing water resources, have made improved efficiency of water and nitrogen management a top research and extension priority for the deciduous crop industries. Pecan tress use more water (14%) than almonds and consequently the pecan trees are one of the highest water use crops among the deciduous tree crops

Currently, there is no model to simulate pecan tree growth under water and nitrogen stress that has been calibrated and evaluated by experimental data. In this study, a pecan growth model was developed that contains nitrogen and a water stress function. The nitrogen function limits tree growth based on leaf nitrogen concentration. Leaf concentration was calculated by nitrogen concentration at the root zone and nitrogen distribution to the tree components. At the same time, evapotranspiration was reduced by nitrogen stress and interacts with the water stress function. The stress functions and their interactions were derived from a physiological mechanistic model and experimental data. The pecan tree growth model was evaluated by experimental data. The evaluation shows that the water stress function is reasonably accurate, while the model may overestimate the nitrogen uptake. More field experiments needed to calibrate the related nitrogen uptake component of the model.

Introduction

Nut production from pecans, almonds, and pistachios figures heavily in the economies of California, Texas, and New Mexico, and several other states. Production depends upon irrigation, but water supplies for irrigation in the near term appears likely to be cut severely in California (15-50% of normal) and surface irrigation water supplies have been reduced in low runoff years in New Mexico. Only the supplies of the surface water supplemented with ground water has allowed the pecan growers to apply full irrigation amounts to the pecan trees. In the long term, both climate change and population growth and diversion of water to municipal and industrial growth will reduce irrigation water supplies.

Water and nitrogen management in deciduous perennial crops is constrained by a lack of related information and an inability to provide targeted management. Currently, the application of fertilizers and water follows standardized practice with little consideration of spatial, temporal, climatic and crop variability resulting in lost income and negative environmental impact. Rising fertilizer prices, water shortages, market and environmental demands, and the recognition that over 50% of the green house gas production can be attributed to N_2O production by agriculture have resulted in great interest in the development of improved management practice. Irrigation amount at less than the levels that maximize yield and/or profits may have to be done in the future because of water shortages and government regulations. It remains possible to set the timing and amounts of irrigation in such a way as to maximize the yield within the season-total constraints on water use. At the same time, the future yield capacity can be preserved and the death of trees prevented. To develop these optimal schedules for a given fractional availability of water, we must understand how the trees respond to deficit irrigation and its detailed scheduling and get quantitative estimates of how water stress changes tree photosynthesis, its partitioning to nut fill, maintenance respiration, net growth, and reserves, and the dynamics of N in leaves, soil, and reserves. This knowledge that must be incorporated into management practices by the development and use of management tools.

Crop modeling in general is a major research tool in horticulture (Gary et al., 1998), with simulation models being used to understand the integration of physiological processes and mechanisms of tree response to stress. Models are also used to interpret experimental results gained under different environmental conditions and to develop and test new production technologies (Pokovai & Kovacs, 2003). Passioura (1996) argues that models fall into two categories: (1) mechanistic models developed for scientific understanding of processes in nature or (2) functional models developed to solve management problems. Mechanistic models are based on hypotheses, which may or may not be correct, of how plants grow. These models often are difficult to run because of the large number of inputs and state variable changes that occur in the models that cannot be measured in the field. On the other hand, functional models are robust and easy to understand and run but are not necessarily applicable outside the environmental conditions that were used in their development. The functional models can illuminate, to a limited degree, the mechanistic aspect of plant growth within the environment under which they were developed.

Tree growth models usually include four main carbon processes: photosynthesis, respiration, reserve dynamics, and carbon allocation (LeRoux et al., 2001). In forestry, over 27 tree growth models have been developed, each with the main carbon metabolism processes described but each having a different representation of these processes—from empirical relationships to mechanistic models of instantaneous leaf photosynthesis—to account for the major environmental variables. Carbohydrate reserve pools are represented as black boxes in the models with no description of their dynamics except that the pools behave like buffers that absorb the excess carbohydrates on a daily basis. Mobilization from the reserve pool occurs as needed for tree growth processes. In the models, the representation of carbon allocation and of the effects of architecture on tree growth are the main limitations of the models, but reserve dynamics are always poorly accounted for, and the representation of below-ground processes and tree nutrient dynamics is lacking in most of the models (LeRoux et al., 2001). These same processes and deficiencies occur in the smaller number of developed fruit and nut tree models. Fruit and nut tree models have been developed for pecans (Andales et al., 2006), apples (Seem et al., 1986), peaches (two models: Lescourret et al., 1998; Allen et al., 2005), and avocados (Whiley et al., 1988)

Models joined with experiments are an excellent way to synthesize what we learn in experiments and then to estimate the best management strategies. Experiments alone are insufficient and inefficient. For example experiments to induce tree responses to water stress are difficult, expensive, and risky - using many replicate trees means using a large area, and it entails a risk of long-lasting damage or death. Furthermore, we need to cover a wide range of climates, interannual variations in weather, soil types, etc. A multifactorial experiment would be wholly impossible. Consequently, limited experiments to parameterize functional model are needed and then verification of the model using limited experimental condition under different climate conditions can be used to verity the model. After model verification, optimal management decision tress can be derived by the model and implemented using rules or simple nomograph for the use by the end user.

Sometimes experiments can be used to parameterize complex submodels such as a mechanistic photosynthesis submodel and then this model used to determine a water use efficiency number to convert evapotranspiration to photosynthesis and biomass in a functional models developed to solve management problems. The submodel can be run independent of the overall plant growth functional model, but the mechanistic submodel generally requires more complex inputs. When developing complex submodels, the models still need to incorporate robust patterns of plant responses to the environment which means response patterns that have been shown to be common among different species and conditions. One very strong example is the relation of leaf photosynthetic rate to CO_2 concentration (partial pressure) inside the leaf and the kinetics of Rubisco enzyme (or, in lower light, a series of photochemical steps all coming down to one parameter, an electron transport capacity). The famed Farquhar - von Caemmerer - Berry model (Farquhar et al. 1980) puts all this into a simple mathematical form. Another robust pattern is in stomatal control through stomatal conductance (gs), the physiological setting of gs by light level, air temperature, CO_2, air pressure, humidity, windspeed, and water stress described by the Ball - Berry equation (Ball *et al*., 1987). The solution of the model requires the simultaneously solution of the Ball –Berry equation, the net assimilation rate equation and the leaf energy balance equation but the model incorporates physiological feedback and feedforward controls.

When developing complex mechanistic submodels, the submodels can be of different complexity. An example is two photosynthesis submodels with different complexity. One submodel can simulate the structure of the canopy, while the other simpler one can only simulate the sunlit and shaded leaf areas as uniform entities. The relation of these sunlit and shaded areas to detailed canopy structure is set, for one particular canopy structure. The simpler model runs much faster and is easier to comprehend. However, it cannot be applied with high accuracy to new canopies of different structure, unless one runs the complex model at least once to parameterize the simpler model again. This parameterization is needed if one is to use them in arbitrary conditions, or, to have the models be transferrable between sites and conditions. The extreme case of non-transferability is the use of a purely statistical model, a fit to data that applies to one site with limited set of conditions.

Although the complex mechanistic submodel may be more transferable than a simpler model, it is "data-hungry," requiring much more information to use it. This may be a realistic expectation - canopies (or systems in general) differ in many details. Some of the details are important for the results that a user is focusing upon, others are not. This leads to another use of complex models - determining which descriptors of the system are important to the results (simulations, predictions) being examined. One can run the complex model with variations in each descriptor, say, foliage density, or root-length density, or average air temperature, and see how much difference each factor makes. For the factors that don't matter much, we can set them as constants in a simple model or otherwise make them unnecessary to specify.

There also remains a hazard in complex models, that of compensating errors. A complex model may describe very many processes, each with descriptions (such as root length density) that may be hard to obtain from experimental data with a level of effort that is affordable. One may make guesses for the poorly-known descriptors, and possibly "tweak" them all to get the right results for a small set of final variables. The results may have come out well only because errors in one description cancelled those in another (or several others). The only way to check for full consistency is to get a wider array of results - say, not just total growth or total nut yield and total water use, but many details of the time courses of transpiration, etc., or more deeply yet, the responses of various leaves. If these data are not obtainable with the effort that one can mount, then one must live with reservations about the full validity of the complex model.

Tree management model should include a pruning submodel that benefits tree growth and optimizes nut production. Figure 1 from Andales et al. (2006) is a flowchart for the pecan tree growth model showing the allocation of growth. Pruning can affect the alternate bearing characteristics of nut trees. Pecan, pistachio, and almond trees show alternate bearing characteristics that need to be described in a nut tree model. In the pecan model, alternate bearing is a function of stored carbohydrate reserves in the beginning of the year. The impact of carbohydrate reserves on nut set, leaf growth, and final nut yield requires further research to determine if the root carbohydrate reserves affect all nut trees as they affect pecan growth, yield, and alternate bearing (Andales et al., 2006).

The pecan nut tree model lacks a fruit abortion subroutine and a nutrient allocation and nutrient stress subroutine. A very simple nutrient balance model that is not mechanistic was developed for almonds (Brown & Zhang, 2008) and represents the state–of-the-art for modeling nut tree nutrient subroutines' effects on nut yield. Most of the fruit and nut tree models have functions that describe the impact of water stress on tree growth, but future nut tree models need to incorporate the interaction of water, nitrogen, and salinity on tree growth and nut yield. However, limited field experiments have been conducted to describe these interactions at the whole tree level. None of the tree models have subroutines to describe the impact of soil-air-oxygen stress caused by prolonged saturation of the soil profile on tree physiology and growth. This will be an important stress function to incorporate into future nut tree models, especially for nuts like pecans that are grown in locations where heavy soils are flood irrigated and water remains on the soil surface for 5 days, which results in a decrease of oxygen levels near a

0 to 50 cm depth that can cause a decrease in photosynthesis (Kallestad et al., 2007). A pistachio tree model is unique in that it will need an object that describes early splitting of nut as a function not of water status but of temperatures lower than 13°C (Gijón et al., 2008).

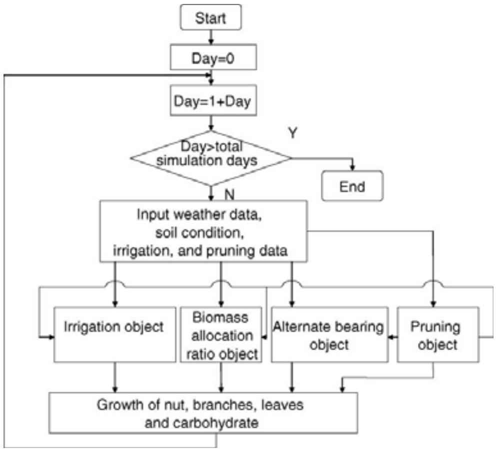

Figure 1. Flowchart of the pecan growth model.

If a tree growth model is built as a user-friendly decision support system, it should include all objects necessary to simulate crop growth using either mechanistic or empirical functional relationships (Reynolds & Acock, 1997). Tree growth models can be built using the traditional method of a main program and a series of subroutines to describe the processes. In this case, the input data is read in through an input subroutine and then information is passed to the other subroutines through common statements. Another programming approach is to develop object-oriented decision support models that contain real-world objects with software counterparts. Each object consists of encapsulated data (attributes) and methods (behavior and interactions). Objects interact with each other and with their environment. Objects also provide interfaces by which users can change attributes or execute methods.

Most computer languages have the ability to program in an object-orientated format, including using an Excel workbook in which each spreadsheet in the workbook can be an object. The advantage of structuring a nut tree model in an object-oriented decision support system is that objects can be added, removed, or changed depending on the model developer's needs. For example, if nutrients are not going to be considered in the model, that object can be removed. As computers and spreadsheet programs have become more powerful, there is no longer a limit to the number of spreadsheet cells that can be used. As a result, spreadsheet nut tree growth models are easy to build and do not require knowledge of FORTRAN or C++ computer languages to change the model. Also, because spreadsheet models do not require compiling, the source code is part of the program and can be either locked to prevent users from changing it or unlocked for future change and development.

With the discussion of the limitation of nut tree model in mind the overall goal of the research was to develop a management model to monitor and predict nutrient demand

and nutrient status in pecan trees along with the interaction of nutrient and water stress on nut yield. Specifically the objective was to develop an optimal schedule (timing and amounts) of irrigation and N fertilization that maximize yield when irrigation water is cut to 50% (or other specified fraction) of normal.

Model description

Because models and submodels can be developed with different complexities a complex mechanistic photosynthesis tree model not including soil water and soil nitrogen balance or growth balance was used to parameterize the water use efficiency, nitrogen stress function, the interaction of water and nitrogen stress in the functional model of pecan tree growth. A description of the function model of pecan tree growth is given by Andales, et al (2006) except for the impact of nitrogen and water stress on water use efficiency and a description of the nitrogen soil transformation and uptake model which will be described latter in the paper.

Description of the complex photosynthesis pecan tree model used to parameterize the pecan tree growth model.

The photosynthesis model resolves the actual structure of the orchard, in which leaves get different light levels. Leaves are in the model are simulated at different angles relative to the direction of the sun, and other leaves intercept part (or all) of the direct sun and part of the diffuse skylight; this includes leaves on neighboring trees, a complexity first addressed by Norman and Welles (1983). The model allows for different three spacing and size with the trees modeled as ellipsoids. The direct solar beam arrives statistically at any spatial location, with a probability calculated by Beers' law and using the real distribution of pecan leaf angles and the total possible obstruction by leaves on all trees between the sun and the location. This is modeled using a probability P_{dir} that the direct beam arrives at full intensity and a probability $1-P_{dir}$ that is completely blocked at this location. The diffuse beam arrives deterministically, at a fraction P_{diff} that is also computed from Beers' law, but applied to beams from 25 different sky directions.

The total leaf cover is resolved into 125 locations within the canopy. Each location is representative of the same volume of canopy (same number of leaves, and same leaf area) as every other location. At each location the total leave cover for that location is portioned into 10 ranges of angles and thus 10 ranges of direct solar radiation relative to the direct solar beam.

Photosynthesis by the whole canopy

The total photosynthetic rate of the canopy is the sum of the rates for all the leaf areas. It would be computationally very inefficient to compute separately the rate for each location and each leaf angle and each class (directly lit or not). Instead, the model adds up, over all locations, the fraction of leaf area in 10 ranges of total light level (called *irradiance*). Then, the model computes the photosynthetic rate (and transpiration rate) for the 10 different irradiances (the midpoint of each irradiance "bin"). Leaves at different locations also see different temperatures, windspeeds, and humidities which are ignored to simplify the model. The average meteorological conditions for the nearby weather station are used to get the average climate variables adjusted to canopy conditions. The time step for the model is 10 minutes but the time step of the available climate data is 1 hr average values.

The complete environment of the leaf determines photosynthesis**.** The leaf photosynthetic rate, A_{leaf}, depends not only on the irradiance (in photosynthetically active radiation between 400 and 700 nm in wavelength), but also on temperature, humidity, CO_2 concentration, and windspeed. There are four basic equations that capture the greatest part of the biophysical and biochemical responses and allow a computation of $A_{leaf,}$ the leaf transpiration rate, E_{leaf}, and the stomatal conductance, g_s:

1) The Farquhar - von Caemmerer - Berry model of A_{leaf} in terms of basic photosynthetic capacity ($V_{c,max}$, related to content of Rubisco enzyme, in essence, and closely related to leaf N content), CO_2 partial pressure at the Rubisco sites (C_i), and leaf temperature.

$$\text{Aleaf} = V_{c,\max} \frac{(C_i - \Gamma)}{(C_i + K_{CO})} \qquad (1)$$

Where : Γ and K_{CO} are temperature-dependent functions for the Rubisco enzyme.

The temperature of the leaf needed to derive Γ and K_{CO} is determined by the equation of energy balance (the sum of all the methods that a leaf can gain and lose energy, and assume that the leaf is always close to steady state) The model accounts for energy gain from radiation - the PAR portion of the spectrum (close to half of solar radiation), the near-infrared portion (NIR; the other half of sunlight), and thermal radiation. The model has already computed how much PAR reaches various amounts of leaf area and it is assumed that the same amount of NIR reaches these leaves. The model will be in error on this part of the calculation because this is a weak approximation. NIR is absorbed much less strongly; it bounces around in the canopy and reaches leaves deeper in the canopy. This bouncing also means that a significant amount of NIR reaches leaves after first scattering off other leaves.

The thermal infrared radiation (TIR) arrives from two main sources- the sky, radiating from water vapor molecules at a range of altitudes, and the other leaves. The model ignore the radiation from the soil surface. TIR is calculated from:

$$\text{TIR} = rT^4 \qquad (2)$$

where :

T is the absolute temperature of the body and
r is the Stef-Boltzmann Constant.

Equation 2 assumes an emissivity of 1 where as leave have an emissivity of 0.98. The effective temperature (T) is assumed to be a fixed number of degrees below air temperature at a weather station which will increase as the pecan leaves become under water or nitrogen stress.

The transpiration rate (E) and evaporative cooling of the leaf depends on the stomatal conductance and a larger boundary-layer conductance, in series, the leaf temperature, and the partial pressure of water vapor in the surrounding air. Because the leaf temperature is part of calculation for the energy balance, the energy-balance equation is solved iteratively. The boundary-layer conductance depends on the leaf linear dimension and on the average windspeed at its location (reference) assumed to be the average wind speed measured at the weather station. The stomatal conductance is calculated from the Ball-Berry equation:

$$g_s = m\frac{A\,h_s}{C_s} + b \qquad (3)$$

Where, A is the leaf photosynthesis rate, A_{leaf},

h_s relative humidity

C_s is the CO_2 mixing ratio at the leaf surface, beneath the leaf boundary layer.

The occurrence of A (A_{leaf})) in equation 3 means that this equation must be solved iteratively with the photosynthesis equation one. This iteration loop represents real physiological feedback and feedforward that occurs in the plant leaves. The values of h_s and C_s depend on A and E of the leaf and on the stomatal and boundary-layer conductance.

Equation 1 also needs C_i calculated from the external CO_2 partial pressure, C_a:

$$C_i = C_a - A\,P_{air} / g_{tot,CO2} \qquad (4)$$

Where: P_{air} is the total air pressure because

$g_{tot,CO2}$ is the total conductance for CO_2 through the stomata and the boundary layer.

Equations 1-4 are solved using a binary search over magnitudes of g_s until all the equations are solved simultaneously. First a guess is made for the value of g_s. The energy-balance equation has all the other quantities specified, the model calculates the leaf temperature using the iteration of procedure. We combine the enzyme-kinetic equation (1), with its parameters corrected for the leaf temperature, and the transport equation (4) to get a single equation for C_i. When we use the form of the enzyme-kinetic equation generalized to handle light-limited photosynthesis, this becomes a quartic equation. We solve it rapidly by iteration. Now we have both C_i and A. Finally, we rewrite the Ball-Berry equation to highlight the error in the solution, as

$$F = g_s - (m\frac{A\,h_s}{C_s} + b) \qquad (5)$$

When we have the right guess for g_s, F becomes zero. We home in on the proper value of g_s by a binary search. We guess the min and max values that g_s could lie between. We compute F at each end, and then for g_s in the middle. The solution has to lie between the values of g_s where F changes sign. We take these two values as the new min and max, thereby halving the interval. We keep doing this until the interval is less than some preset accuracy, say, 0.00001 mol m-2 s^{-1}.

Photosynthesis gross rate is debited for instantaneous respiration in the leaf. This has been found repeatedly, including by us, to be 8 to 10% of gross PS at the current two-week-average air temperature, T_{mean}. We input the latter and calculate the respiration rate for any leaf, applying an exponential factor in actual leaf temperature, $exp(0.07*(T-T_{mean}))$.

The rate of photosynthesis is not to be compared with net CO_2 exchange of an orchard, because respiratory losses of CO_2 (partial undoing of photosynthesis) occur at night everywhere, and at all times in the trunk and in the soil…at a rate that makes net CO_2 uptake as small as 20%, or even 0% or less, of this "canopy gross" photosynthetic rate. The soil respiration is typically largest. It comes from living root tissue, when sugars are metabolized for energy to drive synthesis of new tissue and to maintain all tissue. It also comes from microbes in the soil, using up direct exudation of sugars and acids by the roots (done by the tree for a variety of ecological reasons) and also breaking down dead roots, which arise on a short turnover time from live roots. These corrections need to be made to the output of the model to determine WUE under different water and nitrogen stress conditions.

Limitation of the model. The transpiration by all leaves in the canopy adds humidity to the canopy, changing the environment of the leaves. Also, photosynthesis lowers the CO_2 level in the canopy, and convective energy transfer alters the air temperature in the canopy. Consequently, within the canopy the rate of photosynthesis and transpiration change meteorological conditions as the model iterates the solution for, particularly, the air temperature, T_{air}, and water-vapor partial pressure, e_{air}. At each iteration, the model get a new e_{air} and a new T_{air}…and then new canopy totals of A and E…which gives us new e_{air} and T_{air}. The iterations are prone to oscillate and divergence, and the model consequently limits the changes in e_{air} and T_{air}, from their values in "free" air above the canopy for any iteration, depending on the boundary-layer (or aerodynamic) conductance of the canopy as a whole. This depends inversely on windspeed, with a constant of proportionality that depends on canopy leaf-area index, *LAI.* Windspeed comes from the weather data, and *LAI is* based tree size and spacing and total leaf area. All these processes change in rate over the day, as the solar angles, air temperature, humidity, and windspeed changes.

With this complexity, the model still has left out a number of processes:

* Energy balance of the soil and soil evaporation (this is in the pecan plant model)

* The model assumes a canopy photosynthetic capacity linearly related to nitrogen content in the leaves which has to be change as an input variable over time.

* Rainfall interception is ignored

* Stomatal control parameters, *m* and *b*, are constant. Under water stress, *m* certainly declines and this is being put into the model. The root water potential can be used to estimate the drop in Ball-Berry slope, *m*.

Description of Nitrogen submodel in the Pecan tree growth model.

The nitrogen submodel presented simulates the interaction of nitrogen transformation, soil temperature, water, and nitrogen uptake to describe nitrate distribution in the root zone of a growing crop for the entire growing season. The model requires both a soil water balance submodel and a soil temperature submodel. It is not meant to critically evaluate the individual processes; rather, the model is intended to serve as a management tool for guiding nitrogen fertilizer and water application and for scheduling irrigation. Volatilization and microbial immobilization of nitrogen were not treated in this model: They were assumed to be negligible.

Nitrogen Transformation

Nitrogen transformation is microbial mediated. The process is assumed to occur actively in the top 30 cm of the soil because of a higher concentration of carbon in that layer. Nitrogen transformation is assumed to follow irreversible first-order rate kinetics proposed by Mchran and Tanji (1974) as

$$\frac{dN}{dt} = -KN \qquad (6)$$

where N is the concentration of nitrogen specie (substrate) in question, dt is the time interval, and K is a rate constant.

Hydrolysis

Hydrolysis is one of the nitrogen transformations. The process involves the conversion of urea into ammonium. Hydrolysis is assumed to occur within days so that applied urea is quickly converted to ammonium.

Mineralization

Mineralization of organic matter to ammonium is modeled based on the modification and the rearrangement of the first order kinetics equation developed by Stanford and Smith (1972) and Stanford et al. (1973) and presented by Stockle and Campbell (1989) and Watts and Hanks (1978) as

$$M = (M_0(1 - exp(-K_m t)))F(fps) \qquad (7)$$

Where M is nitrogen mineralized (K_g N m^{-2}) in time t (day) at the corresponding soil water content; M_0 (K_g N m^{-2}) is the potentially mineralizable nitrogen at the start of the time interval t ; K_m is the mineralization rate constant (day^{-1}); and F(fps) is a function of soil moisture. Using the work by Stanford and Epstein (1974) and Pilot and Patrick (1972), the function (*fps*) was described by Watts and Hanks (1978) as

$$F(fps) = 1.111fps; 0.0 \le fps < 0.9 \qquad (8)$$

$$K_n = K_{n35}(0.0105T_s + 0.00095T_s^2); 0°C \le T_s < 10°C \qquad (9)$$

$$K_n = (0.032T_s - 0.12)K_{n35}; 10°C \le T_s < 35°C \qquad (10)$$

$$K_n = (-0.1T_s + 4.5)K_{n35}; 35°C < T_s < 45°C \qquad (11)$$

Where K_n is the nitrification rate constant) (day^{-1}); T_s is the soil temperature in ℃; and K_{n35} is the rate constant at 35 ℃.

Denitrification

Denitrification of nitrate is modeled along the same pattern as nitrification proposed by Stockle and Campbell (1989):

$$D = D_0(1 - exp(-K_d)) \qquad (12)$$

Where D is the amount of nitrate denitrified (kg NO_3 m^{-2}) in time t;D_0 (kg NO_3 m^{-2}) is the amount of nitrate available at the beginning of the time interval t; and K_d (day^{-1}) is the denitrified rate constant. The Denitrification rate constant is corrected for soil water content and temperature as proposed by Greene (1983):

$$K_d = exp(0.08(T_s - 15))K_{d15}F(\theta_i) \quad \text{for} \quad T_s \leq 10°C \qquad (13)$$

$$K_d = 0.67\,exp(0.43(T_s - 10))K_{d15}F(\theta_i) \quad \text{for} \quad T_s > 10°C \qquad (14)$$

Where K_{d15} is the rate constant at 15°C; T_s is the soil temperature in ℃; and $F(\theta)$ is water content correction function for denitrification, defined as

$$W = 47(\theta_s - \theta)^2 \qquad (15)$$

$$F(\theta) = exp(0.304 + 2.94(\theta_s - \theta) - W) \qquad (16)$$

Where θ_s and θ are saturated current volumetric soil moisture content, and W is a variable.

Average soil temperature on any day needed by the rate functions is modeled based on the method developed by Jones and Kiniry (1986) and then modified by Sharma et al. (2009). The method requires daily maximum and minimum air temperature, solar radiation, soil bulk density, and moisture content and percent cover estimated from a crop coefficient used to calculate evapotranspiration in the soil water balance subroutine.

Nitrogen uptake

The mechanistic N transport and uptake model is based on model by Yanai (1994) that actively take N from the soil water, transport it into the xylem and into the leaves where N transformation will occur into organic N or stored as nitrate. The organic N level will control the photosynthesis rate and stomatal resistance, which in turn will control the transpiration rate and biomass growth including nut yield (Gutschick 2007).

Nitrogen uptake (U) in the model is defined by equation 17.

$$U = 2\pi r_\circ L \alpha C_\circ \Delta t \qquad (17)$$

Where: $2\pi r_\circ L$ = the surface area of the roots.

Δt = time step.

α = a rate uptake constant which is calculated from a Michaelis-Menton equation that decrease uptake as the concentration at the root surface increases.

$C_\circ$ = concentration of solute at the root surface calculated from the average concentration in the bulk solution C_{av} is described by equation 18.

$$C_\circ = P_c C_{av} \qquad (18)$$

P_c is a function of the inward velocity of water at the root surface, the radius of the root, the average radial distance from the center of the root to the next root's zone of influence, the effective diffusion coefficient of the solute through the soil.

In order to solve equations 17 and 18 knowledge must be known about the root length density of both the old and new roots along with the nitrogen concentration in the bulk soil water nitrogen transformation submodel and the water balance submodel. Nitrogen is then partitioned into the roots, trunk, branches, and leaves based on the carbohydrate allocation to each part. When the leaf nitrogen content falls below 2.72%, nitrogen stress occurs and photosynthesis and evapotranspiration will decrease according to a function reported by Sparks and Baker (1975) and by the complex photosynthesis tree model described by equations 1-5.

Material and methods

If trees or other plants are given reduced and water supplies, many physiological acclimations occur with the first response of the tree to be a reduction in stomatal conductance, g_s. This cuts leaf transpiration almost in proportion - not quite as much, because leaf cooling is reduced, and the rise in temperature raises the leaf-to-air gradient in water-vapor pressure. The reduction in g_s also cuts leaf photosynthesis, but considerably less than proportionally - the stomatal resistance (inverse of conductance) is a much smaller part of the total pathway resistance for incoming CO_2. Consequently, water-use efficiency (WUE), as the ratio of photosynthetic rate to transpiration rate, rises. Measurements of water use efficiency under non-water stress conditions have been previously be made (Wang et al. 2007) to verify both the complex photosynthesis model and the simple pecan plant grow model. The complex photosynthesis model was calibrated again in two dry down irrigation cycles imposed on a pecan orchard near Las Cruces, NM to verify the model under moisture stress conditions and against selected pecan trees in the same orchard showing nitrogen and water stress conditions. The complex photosynthesis model was then run under moistures and nitrogen stress conditions to develop the WUE function vs. plant water potential and leaf nitrogen level used in the whole pecan plant model. The nitrogen stress function was incorporated into the pecan tree functional model that was then tested against a separate water nitrogen stress experiment in another climate environment in Oklahoma (Smith et al 1985). The pecan trees at the Oklahoma study site only received rainfall, and nitrogen amounts from 0 to 265 kg/ha. The climate data was acquired from NCDC for Stillwater Oklahoma 16 km north of Perkins Oklahoma where the study was conducted. There was no statistical difference in the pecan yield each year for the different fertilizer treatments so the mean yield each year for all the treatments was used in the comparison to the model prediction of yield.

Results

The photosynthesis pecan model's relative change in transpiration occurs linearly as leaf N decreases expressed as a relative value of the 2.8% nitrogen starting point (Nr) under water stress condition when E was 50% of E non-stressed (Figure 2). Modeled WUE also decrease linearly with a decrease in relative N because the leaf temperature rises when Photosynthesis capacity is lowered due to nitrogen stress conditions in the leaves. When water is not limiting decrease in transpiration caused only by nitrogen stress also resulted in leaf temperature to rise by 3 °C. A decrease in N level causes a decrease in WUE and relative E(Er). The measured relative decrease in growth related linearly to relative E from the experiment by Sparks and Baker (1975) agrees with the model simulation of pecans under both nitrogen and water stress until the nitrogen level becomes less than 1.66% nitrogen at which time the relative transpiration decreases as a non-linear function (Figure 2). The functions of WUE vs. nitrogen and E vs. nitrogen can be:

$$Er = 0.7134\ Nr + 0.326 \qquad (19)$$

Coefficient of determination = 0.9865

$$WUE = 0.4059Nr + 0.6015 \qquad (20)$$

The coefficient of determination = 0.9971

Consequently, the interaction between nitrogen stress and water stress on evapotranspiration (Et) in the pecan growth model is multiplicative:

Et= Etns* soil water stress function* nitrogen stress function. (21)

where Etns is the non-stressed Et.

The nitrogen stress function is from Figure 2 (equation 19) and the water stress function is:

$$Et/Etns= 0.5RAW \qquad (23)$$

Where: RAW is relative available water.

All the N values are "photosynthetically active N. Consequently, it was assumed that 0.3% is the structural part of leaf N added to the non-structural N used by the model.

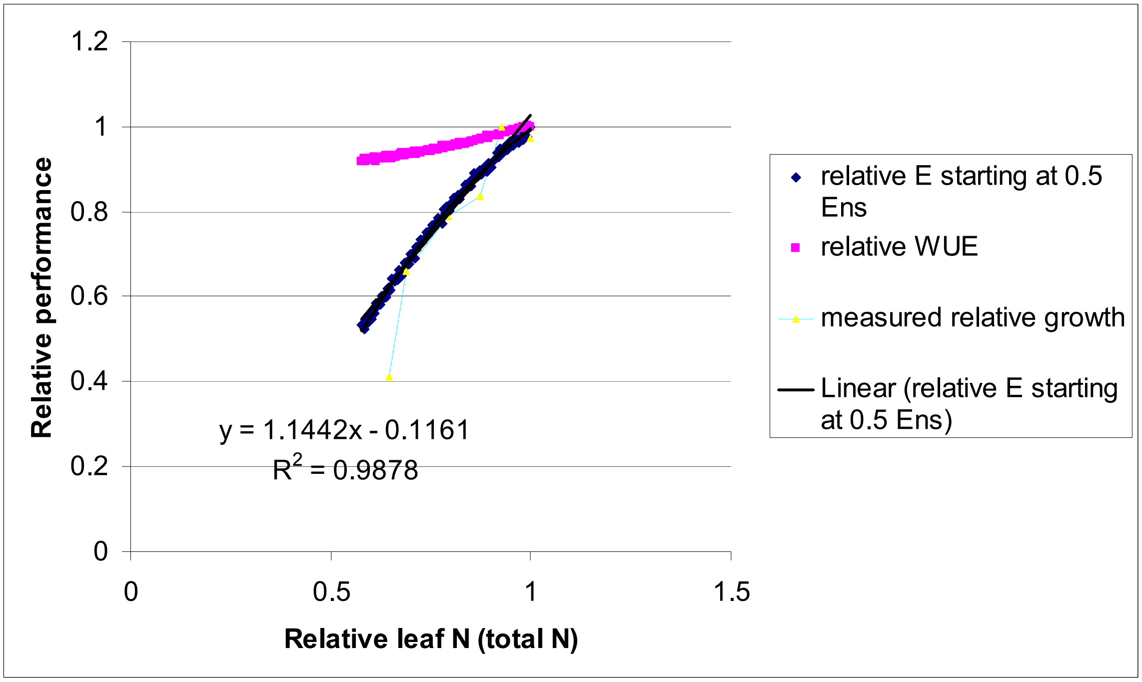

Figure 2. Modeled relative N of total N (0.3% is the structural part of leaf N) vs. relative transpiration, relative WUE and measured relative growth under water stress conditions (Sparks and Baker, 1975) .

The pecan tree growth model was run using the climate data from Stillwater, Oklahoma and both 0 and 260 kg/ha of nitrogen was applied respectively throughout the growing season. The model, same as the measured data, did not show any response to the application of nitrogen because the water stress decreased evapotranspiration and growth sufficiently that the mineralization rate was sufficient to supply the nitrogen need by the pecan trees under the water stress conditions. The nitrogen stress function was the same for 0 and 260 kg/nitrogen (Figures 3 and 4).

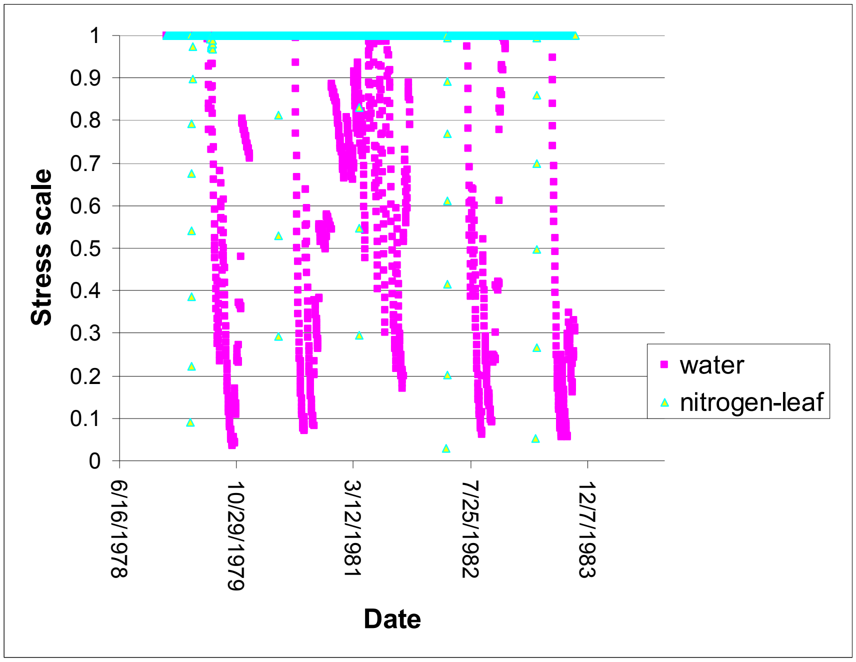

Figure3. Stress response output from Pecan Growth Model when 260 kg/ha of nitrogen was applied through the growing season at Stillwater, Oklahoma.

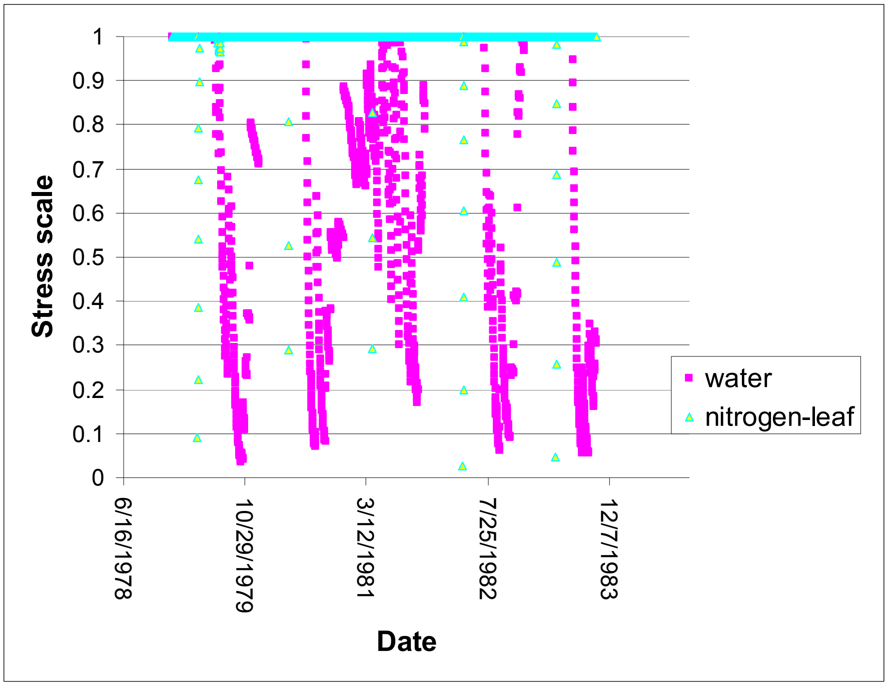

Figure 4. Stress response output from Pecan Growth Model when 0 kg/ha of nitrogen was applied through the growing season at Stillwater, Oklahoma.

The nut yield simulation data under non-water moisture stress where irrigation was applied when moisture stress started to occur ranged from 4500 kg/ha to 3200kg/ha but under rainfall conditions (the actual experimental conditions) the model overpredicted yield by 453 kg/ha in 1979 to under estimation by 703 kg/ha in 1983 (Figure 5). The overestimation in 1979 was due to the initial conditions in the model. A crop simulation model needs to be run for several years prior to the measured data years so that initial conditions can stabilize. In 1983 the water stress could have been greater than at the research site because the rainfall and climate data was from a site 16 km north of the research site which is sufficient distance for a thunderstorm to occur at the research site and not at the weather station site.

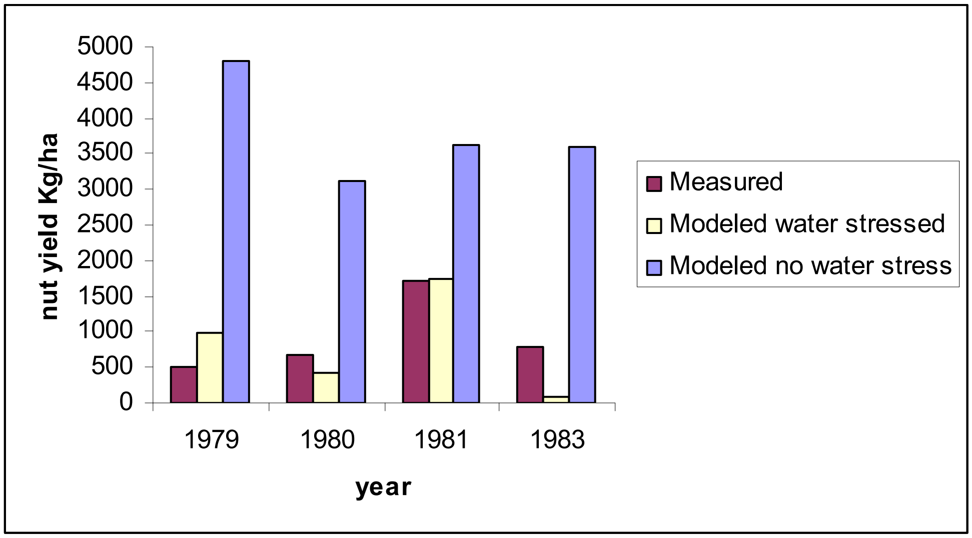

Figure 5. Modeled and measured pecan yield at Oklahoma. Nitrogen was not limiting growth but growth was severely limited by water stress.

A decrease in WUE was not incorporated into the model because the decrease with water stress would have decreased yield even more compared to the measured values. Additional experimental research is needed to verify the mechanistic model estimate of a function of WUE decrease with nitrogen stress before incorporating this function into the pecan plant growth model. The nitrogen content in the model only calculated nitrogen stress when the leaves have below 0.028 g N/g leaf which only occurs when the leaves are just emerging and the nitrogen comes from the carbohydrate reserve pool. As soon as the leaves were budded out then sufficient nitrogen occurred to satisfy the growth of the leaves because of reduced growth due to water stress. The modeled nitrogen content of the leaves increased rapidly to above the 0.028 g N/g leaf (N stress threshold level) but these modeled content was above the measured content with ranged from 0.02 -0.024 in the middle of July (Figure 7). Consequently, based on the leaf nitrogen content there should have been a response in nut yield to nitrogen application but this did not occur in the experimental results. Consequently, it appears that the nitrogen content predicted by the model even under nitrogen stress may be too large but also that the nitrogen stress threshold level derived from seedling experiments in Sparks and Baker (1975) may be too high for pecans. Additional research is needed where mature trees are placed under nitrogen stress and leaf photosynthesis measurements taken to derive the threshold level for mature trees.

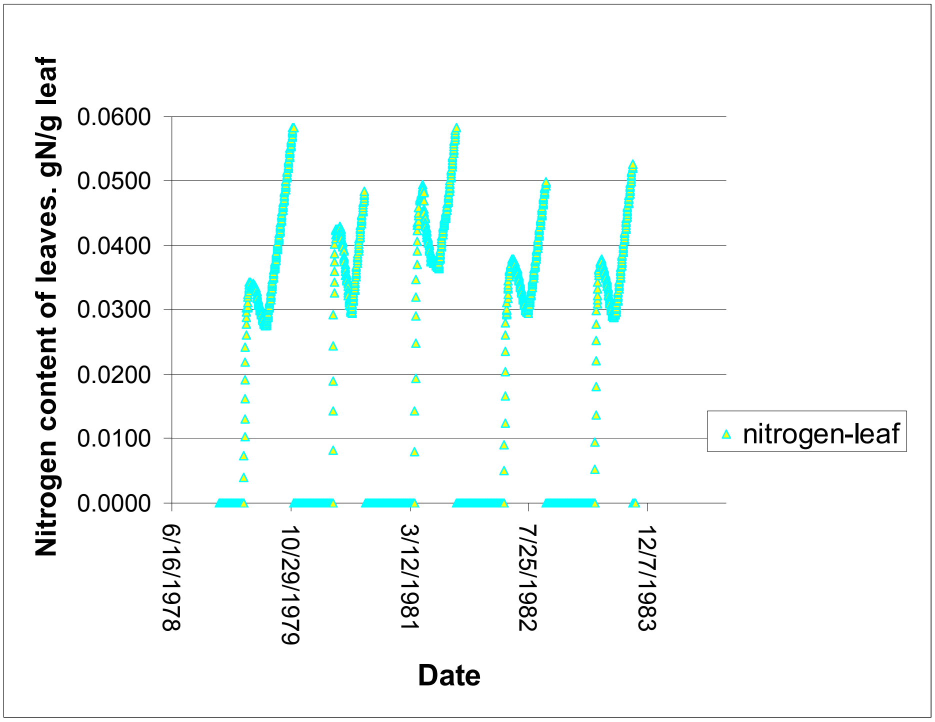

Figure 6 Modeled nitrogen content in leaf with 0 nitrogen application.

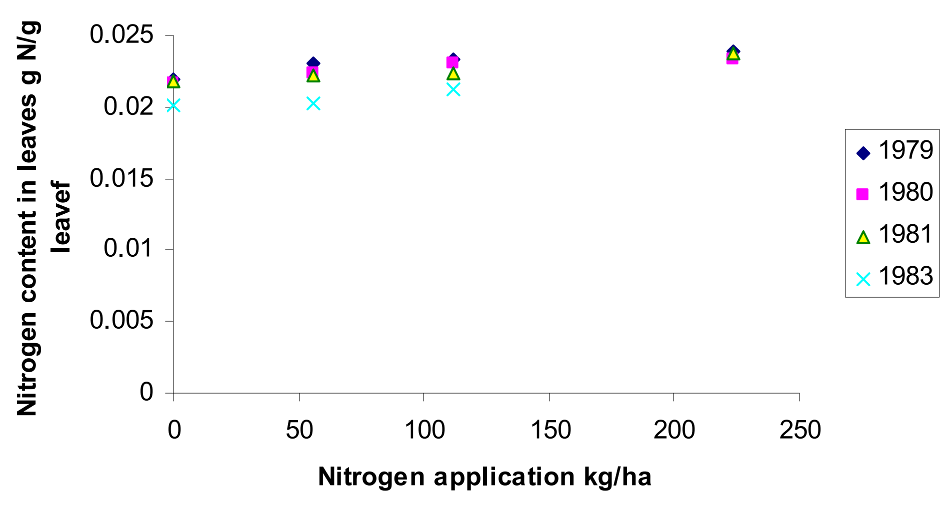

Figure 7. Measured nitrogen content in leaves during the middle of July.

Conclusion

Because nut trees are perennials and the previous year's management can have an impact on nut yield three to four years in the future, a modeling approach to understand the physiological response of a nut tree to inputs of water, nutrients, salinity, cultivation, and pruning offers the only way to understand the complex interaction of these management decisions on nut production. However, any tree model must be verified by controlled field experiments under different environmental conditions. The future of nut tree models will be the development of realistic modules that can be linked together quickly to build a nut tree model appropriate for the management options available to growers. Also, building models using spreadsheet tools will allow more researchers and students to become involved with the development of tree models without having to become computer programmers. The current pecan growth functional model appears to simulate water stress reasonably well but may overestimate the nitrogen uptake and the threshold level of nitrogen stress in the model may be larger than the true value. More field experiments need to be conducted to calibrate the related parameters.

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Sub-surface drip irrigation fertigation for site-specific, precision management of cotton

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Abstract. *A subsurface drip irrigation study was installed at the Tennessee Valley Research and Extension Center in 2006 to evaluate the effect of four precision fertigation management scenarios and a non-fertigated control on cotton yield, nutrient uptake and lint quality. Approximately 7,500 feet of SDI tape and four positive displacement liquid fertilizer injectors were used to evaluate five nutrient timing treatments with four replications in a randomized complete block design. Each of the twenty treatment plots was made up of eight, 345-foot rows of cotton on 40-inch row spacing, with drip tape between every other row of cotton.*

In 2006, fertigated cotton yields were significantly higher than the surface-applied control. In 2007 and 2008, however, yield in surface-applied control was significantly higher than the fertigated treatments. The better non-fertigated control yield in 2007 and 2008 was possibly due to beneficial downward movement of surface-applied fertilizer as a result of early season rainfall in 2007 and possibly the leaching of fertigated nutrients beyond roots zone as a result of heavy seasonal rainfall in 2008.

Fertigated cotton yields averaged 3.0, 2.9 and 3.5 and the control yields averaged 2.7, 3.1 and 3.9 bales/acre in 2006, 2007 and 2008, respectively.

Generally, surface sidedressing enhanced nutrients uptake better than fertigation but none of them had a direct effect on cotton fiber qualities.

These results show that surface sidedressing and fertigation are not mutually exclusive under rainfed cotton production and the observed responses to SDI fertigation were directly related to the amount and distribution of rainfall during the seasons.

Keywords. Subsurface drip irrigation, fertigation, fertilizer sidedressing, rainfall, cotton yield

Introduction

While the southeastern U.S. has plenty of water available on an average annual rainfall basis, large inter-annual variability in rainfall and frequent dry periods during the growing season make purely rain-fed agriculture a poor competitor to the efficiency of irrigated agriculture (Dougherty et al., 2007). The research presented in this paper is located in northern Alabama in the Tennessee Valley, an area of widespread cotton production. Average annual rainfall in Alabama, is about 55 inches per year (AWIS, 2008). However, because of poor distribution, less than 40% of this amount typically falls during the April to August cotton growing seasons. Under recurring periods of water deficit, irrigation to meet crop water requirements prevents potential yield loss.

Prior studies have shown that drip or sprinkler irrigation increased seed cotton yield compared to rainfed cotton yield (Camp et al., 1994; Camp et al., 1997; Bronson et al., 2001; Pringle and Martin 2003; Sorensen et al., 2004; Kalfountzos et al., 2007). However, Camp et al., (1997) and Bauer et al. (1997) in a four-year study found that cotton did not respond to drip irrigation in two seasons presumably as a result of insufficient amount of irrigation water applied. Similarly, Camp et al. (1999) found that subsurface drip irrigation (SDI) did not increase cotton yield because of root growth was restricted above the SDI line by a soil hard pan.

In addition to water application, sprinkler or SDI systems can be used to precisely apply soluble pesticides and fertilizers to minimize environmental impact due to leaching and runoff. Application of fertilizer nutrients through irrigation systems (fertigation) increases seed cotton yield, water use efficiency and nutrient uptake (Janat and Somi 2001a, b; Janat, 2004; Enciso-Medina et al., 2007; Thind et al. 2008). Drip and other irrigation systems permit multiple injections of small doses of fertilizers at different intervals, reducing the risk of leaching compared to fertilizers applied in a single application. Notwithstanding, Hunt et al. (1998) found that sidedressing of N using drip irrigation in a single application produced the highest seed cotton yield compared with five split drip-applications. Similar results have been reported by Hou et al. (2007) for N applied at the beginning of the irrigation cycle rather than N applied in more frequent, smaller doses throughout the irrigation cycle. Bauer et al. (1997) found that N application method (single versus five split drip-applications) through SDI had no effect on cotton yield.

Therefore, objective of this study was to evaluate the effect of four precision fertigation management scenarios and a non-fertigated control on cotton yield, nutrients uptake and lint quality.

Materials and Methods

A subsurface drip irrigation (SDI) and fertigation study was initiated in 2006 at the Auburn University Tennessee Valley Research and Extension Center (TVREC), in Belle Mina, Alabama. The study was designed to evaluate four precision fertigation management scenarios and a non-fertigated control on cotton (*Gossypium hirsutum* L.). Individual fertigation treatments were described in Table 1. Approximately 7,500 feet of SDI tape and four positive displacement fertilizer injectors were being used to evaluate four replications of five nutrient timing treatments. Each of the resulting twenty treatment plots was made up of eight 345-foot rows of cotton on 40-inch row spacing, with drip tape between every other row of cotton (Figure 1).

Table 1. Treatment description in fertigation management trials, 2006-2008.

Treatment	Description
1. Control - drip irrigated, but all fertilizers are surface applied.	Preplant - N and K @ 60 pounds per acre. Post-Plant N (75lb/A) sidedressed at early square.
2. Drip timing 1 – with surface preplant	Preplant - 20 pounds of N and K (surface). Drip 40 pounds N, K –square to bloom (25 days) Drip 75 pounds N, K – bloom to 25 days
3. Drip timing 1 – no preplant	Planting Drip - 20 pounds N, K Drip 40 pounds N, K–square to bloom (25 days) Drip 75 pounds N, K – bloom to 25 days
4. Drip timing 2 – no preplant "spoon-fed"	Planting Drip - 20 pounds N, K Drip 40 pounds N, K square to bloom (25 days) Drip 75 pounds N, K – bloom to 40 days
5. Drip timing 2 – with surface preplant	Preplant - 40 pounds of N and K (surface). Drip 95 pounds N, K–square through bloom (50 days)

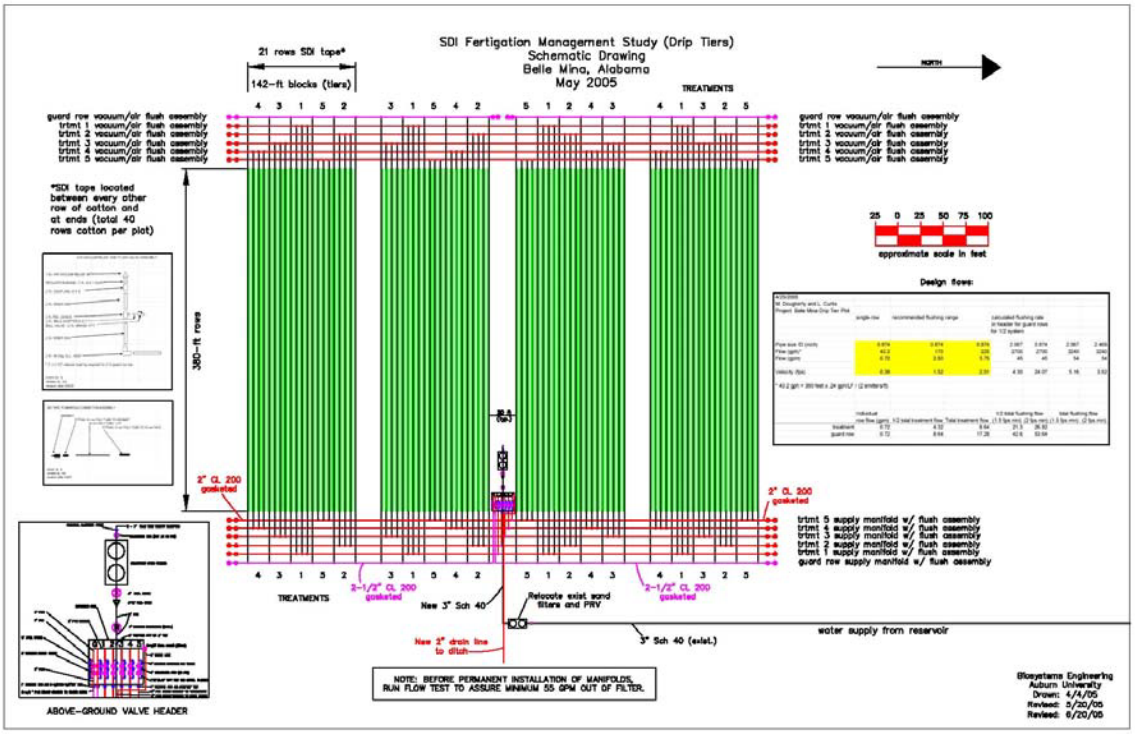

Figure 1. Design layout for drip tier fertigation management study, Belle Mina, AL, 2006-2008.

Emitters were located 24 inches along the tape with tape buried approximately 12-15 inches between every other two rows, providing four harvested rows per treatment for yield comparisons. Spacing between drip tape and two rows was 20 inches, similar to an agricultural field using an alternate row drip tape spacing of 80 inches. Rows 345 feet in length were used to better approximate field operational conditions (Figure 1).

A NETAFIM SDI tape was used in this study with the following specifications: 0.874” internal diameter, 15 mil wall thickness, 24” emitter spacing, 0.24 gph emitter flow rate, and 10 psi operating pressure.

The flow rate of the SDI tape was evaluated at least twice per season typically at the beginning and end of the growing season, after system flushing and cleaning. Flushing and cleaning operations were conducted using both chlorine and hydrochloric acid solutions.

Fertilizer was applied using two methods; 1) surface via conventional sidedress and 2) subsurface via fertigation. Sidedressing and fertigation treatments were applied as described in Table 1. All other farm cultural management practices were carried out according to standard agronomic recommendations from Auburn University.

All treatments received 135 pounds per acre of nitrogen (N) and potassium (K_2O), 20 pounds per acre of sulfur, and l.0 pound per acre of boron. Phosphorus fertilizer was surface-applied to maintain P at high soil test levels. Drip fertilizer, 8-0-8-1.2S-0.06B, was made using 32% liquid N, potassium thiosulfate, fertilizer grade KCL, solubor, and water.

Cotton variety, DPL 445 BR, was planted in each year. Planting was carried out in April each season by row unit planters in rows at 40" and 4" as inter-row and inter-plant spacing, respectively.

Leaf sampling was carried out by taking 4th or 5th fully-expanded leaf from the growing apices of plants in the middle of the plots for all treatments during middle-bloom stage. About 30-40 leaves per treatment were collected while walking directly above an SDI drip line. Leaf nutrient analysis was carried out according to the methods of Auburn University Soil-Plant Testing Laboratory.

Since each treatment was applied to eight rows of cotton, two rows of cotton on each side of the plot were treated as an unharvested border or guard row. The four middle yield rows were harvested by a cotton picker after removing 3 feet from both ends of each row and weighed using a boll buggy equipped with electronic load cells to measure accumulated seed cotton yield per plot. Average post-harvest turnout from the gin was used to determine lint yield and subsequent lint quality analysis was determined in normal ginned cotton samples by USDA, AMS Cotton and Tobacco Programs, Birmingham Classing Office.

The experimental layout was a randomized complete block design with 5 treatments and 4 replications (Figure 1). Yield data for each season was analyzed statistically using a Statistix 8 (Analytical Software, 2003) and Tukey's method at $\alpha = 0.10$ for treatments comparison.

Results and Discussion

2006 season results: Cotton was harvested on October 10 and on October 24, 2006 and evaluated for yield, quality, and leaf nutrients. Results (Figure 2 and Tables 2) indicate differences in cotton yield, quality, and leaf nutrients by treatment. Fertigated cotton yields were significantly higher ($\alpha = 0.1$) than the non-fertigated control (treatment 1). In 2006, higher yields were observed where all fertigated nutrients were applied within 50 days of square. Fertigation treatments 2 and 5, the two highest yielding treatments, received 20 and 40 pounds, respectively, of preplant surface nitrogen and potassium (K_2O). The "spoon-fed" treatment 4 that received no preplant nitrogen and potassium produced the lowest but statistically (α = 0.1) comparable yield to treatment 3 and 5. Plant uptakes for N and P for all treatments were statistically (α = 0.1) the same. Magnesium uptake was significantly (α = 0.1) higher in non-fertigated control than fertigated treatments. No consistent uptake pattern was observed for K and Ca uptake. No statistical differences (α = 0.1) were observed among treatments on lint qualities except for the highest micronaire value in the non-fertigated control. Fertigated cotton yields averaged 3.0 bales in 2006.

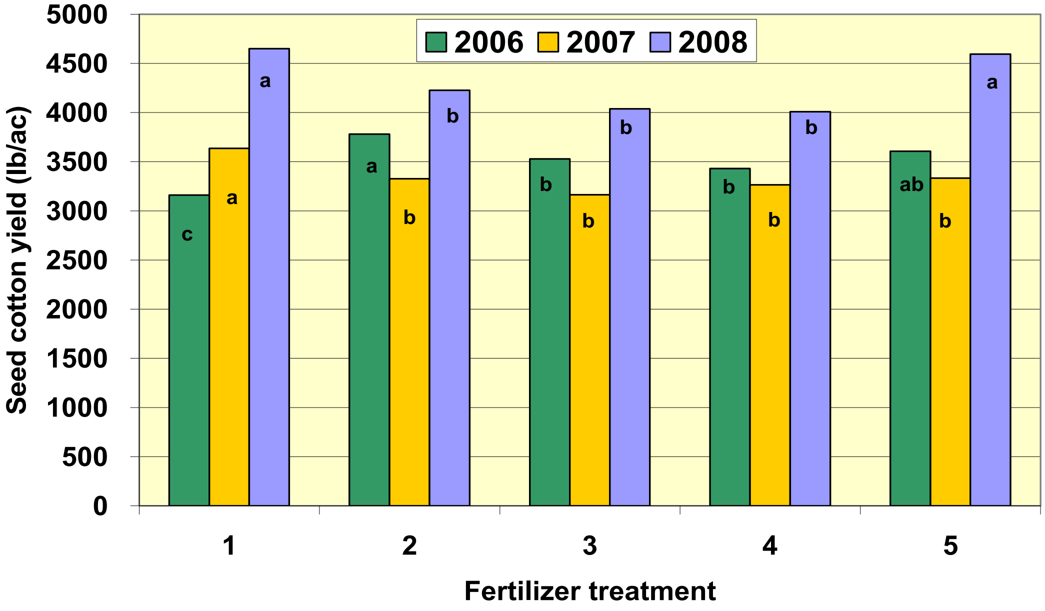

Figure 2. Seed cotton yield in drip tier fertigation management study, Belle Mina, AL, 2006-2008. Different subscripts within a year denote statistical difference (α = 0.10).

Table 2. Lint yield and quality analysis in cotton fertigation management trials, 2006.

Trt*	Bales/ac	Micro-naire	Length (in)	Strength (g/tex)	Uniformity (%)	N%	P%	K%	Ca%	Mg%
1	2.7c	4.83a	1.13a	31.1a	84.3a	3.88a	0.28a	1.48a	2.06a	0.35a
2	3.2a	4.63b	1.15a	30.8a	84.4a	3.92a	0.29a	1.46a	2.01a	0.31b
3	3.0b	4.60b	1.12a	30.6a	84.2a	3.62a	0.24a	1.28b	1.87b	0.32b
4	2.9b	4.65b	1.13a	30.1a	83.8a	3.59a	0.30a	1.44a	2.07a	0.31b
5	3.1ab	4.58b	1.13a	30.2a	83.9a	3.80a	0.26a	1.32b	1.87b	0.32b

*1. Surface applied N-P-K with drip irrigation (control). 2. Preplant 20# N-K surface with 2 N-K drip timings. 3. 20# N-K drip at planting with 2 N-K drip timings (to 25 days after bloom). 4. 20# N-K at planting with 2 N-K drip timings (to 40 days after bloom). 5. Preplant 40# N-K surface with 1 N-K drip timing (square through bloom). Different subscripts denote statistical difference ($\alpha = 0.10$). Turnout = 41%.

2007 season results: Cotton was harvested on October 2, 2007 and evaluated for yield, quality, and leaf nutrients. Results in Figure 2 and Table 3 indicate differences in cotton yield, quality, and leaf nutrients by treatment. The non-fertigated control (treatment 1) was the highest yielding treatment in 2007 and was significantly different ($\alpha = 0.1$) from all fertigated treatments. All fertigated treatments gave statistically ($\alpha = 0.1$) similar yields. Except for P, the plants from this highest yielding treatment had significantly ($\alpha = 0.1$) higher levels of uptake for N, K, Ca, and Mg than fertigated treatments (treatments 3 and 4). Fertigated treatments (treatments 2 and 5), received 20 and 40 pounds of preplant surface nitrogen and potassium (K_2O), showed higher N and K uptake than the two treatments receiving no preplant nitrogen and potassium (treatments 3 and 4). No statistical ($\alpha = 0.1$) effect was noted for all treatments on lint qualities (Table 3). Fertigated cotton yields averaged 2.9 bales in 2007.

Table 3. Lint yield and quality analysis in cotton fertigation management trials, 2007.

Trt*	Bales/ac	Micro-naire	Length (in)	Strength (g/tex)	Uniformity (%)	N%	P%	K%	Ca%	Mg%
1	3.1a	4.40a	1.11a	31.12a	83.98a	4.64a	0.44c	1.74a	3.30a	0.57a
2	2.8b	4.52a	1.11a	30.72a	84.22a	4.12b	0.54a	1.58ab	3.09ab	0.42bc
3	2.7b	4.48a	1.10a	29.62a	83.85a	3.95b	0.47bc	1.47b	2.84c	0.39c
4	2.8b	4.45a	1.09a	30.80a	83.92a	3.49c	0.49b	1.48b	2.99bc	0.41bc
5	2.8b	4.40a	1.12a	30.88a	84.35a	4.14b	0.47bc	1.57ab	3.08ab	0.44b

*1. Surface applied N-P-K with drip irrigation (control). 2. Preplant 20# N-K surface with 2 N-K drip timings. 3. 20# N-K drip at planting with 2 N-K drip timings (to 25 days after bloom). 4. 20# N-K at planting with 2 N-K drip timings (to 40 days after bloom). 5. Preplant 40# N-K surface with 1 N-K drip timing (square through bloom). Different subscripts denote statistical difference ($\alpha = 0.10$). Turnout = 41%.

For 2006 and 2007, two of the driest consecutive years on record at TVREC, fertigated yields were lower in 2007 than in 2006 (Figure 2). In 2007, plant tissue nutrients were generally higher in the highest yielding treatments (Table 3). In 2006, the surface-applied control had levels of plant tissue N, P, and K comparable to the highest yielding fertigated treatment (Table 2). Chemical movement of surface applied fertilizer early in the season was enhanced in 2007 due to 7 storms averaging 0.65" from May through July. Comparable storm events in 2006 delivered 0.41" per event. In spite of comparable seasonal rainfall for 2007 and 2006 (Figure 3) early season rainfall in 2007 assisted delivery of surface-applied nutrients. In addition, several large convectional storms later in the 2007 moved surface-applied nutrients lower into the horizon, potentially leaching fertigated nutrients out of reach of roots.

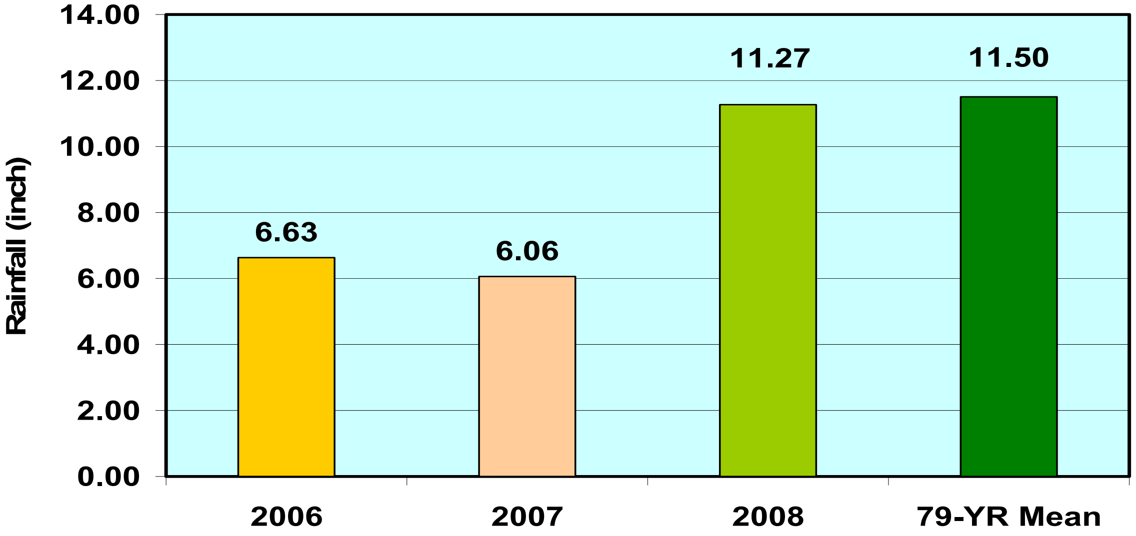

Figure 3. Total seasonal rainfall during June, July, and August period vs. 79-year average.

2008 season results: Cotton was harvested on October 13, 2008 and results are shown in Figure 2 and Table 4. Total seasonal rainfall at TVREC (Figure 3) during June-August period for 2008 was 11.27", which was near normal average (11.50"), and thus seed cotton yields for this season were exceptionally higher than in 2006 and 2007. However, the pattern of response to fertilizer treatments in 2008 is similar to 2007 (Figure 2). In this season, the 100% fertigated treatments (treatment 3 & 4) produced significantly ($\alpha = 0.1$) lower yields than treatment 1 (100% surface-applied) and treatment 5 (30% surface + 70% drip) and they gave comparatively lower yield (Figure 2) than treatment 2 (15% surface + 85% drip). The non-fertigated control treatment and the fertigated treatments that received surface-applied, preplant nitrogen and potassium (K_2O) responded much better in 2008, possibly due to sufficient rainfall and better downward movement of surface-applied fertilizer. However, higher rains may have also resulted in leaching fertigated nutrients farther out of the root zone. This may also explain the plant yellowing and the less vegetative growth observed in treatments 3 and 4 during the season. Soil compaction impeding root growth towards fertigated nutrients cannot be ruled out since the experiment is conducted in a no-till field. Statistically, treatment 1 was the best yielding treatment in 2007 and 2008 whereas treatment 3 and 4 were the least yielding.

Cotton lint yield (bales/acre), lint quality parameters, and leaf nutrient analyses for 2008 are presented in Tables 4. None of the quality parameter was significantly ($\alpha = 0.1$) affected by different fertilizer treatments except for lint length. Lint length in the 100% fertigated treatments (treatment 4) was significantly ($\alpha = 0.1$) higher than the fertigated treatments that received surface-applied, preplant nitrogen (N) and potassium (K_2O). Plant uptake for N and K was significantly ($\alpha = 0.1$) higher in the surface-applied control treatment (treatment 1) than the fertigated treatments with or without surface application. Higher seasonal rainfall in 2008 may have assisted delivery of surface-applied, preplant N and K. Phosphorus, Ca, and Mg contents were not significantly affected by any treatment.

Table 4. Lint yield and quality analysis in cotton fertigation management trials, 2008.

Trt*	Bales/ac	Micro-naire	Length (in)	Strength (g/tex)	Uniformity (%)	N%	P%	K%	Ca%	Mg%
1	3.9a	4.62a	1.10b	27.2a	84.2a	4.32a	0.28a	1.20a	2.27a	0.26a
2	3.5b	4.78a	1.07c	27.2a	83.2a	3.36c	0.27a	1.09b	2.22a	0.26a
3	3.4b	4.75a	1.11ab	28.5a	84.1a	3.24c	0.28a	1.13b	2.26a	0.25a
4	3.3b	4.58a	1.13a	28.4a	84.5a	3.35c	0.30a	1.14b	2.36a	0.26a
5	3.8a	4.65a	1.09bc	28.9a	84.0a	3.57b	0.28a	1.13b	2.28a	0.26a

*1. Surface applied N-P-K with drip irrigation (control). 2. Preplant 20# N-K surface with 2 N-K drip timings. 3. 20# N-K drip at planting with 2 N-K drip timings (to 25 days after bloom). 4. 20# N-K at planting with 2 N-K drip timings (to 40 days after bloom). 5. Preplant 40# N-K surface with 1 N-K drip timing (square through bloom). Different subscripts denote statistical difference ($\alpha = 0.1$). Turnout = 40%.

Although this study did not include a rainfed control, the high yield obtained is likely due to supplemental irrigation provided by SDI system. The beneficial cotton yield response to irrigation during insufficient growing season rainfall has been reported by several researchers (Camp et al., 1994; Bronson et al., 2001; Pringle and Martin 2003; Sorensen et al., 2004; Kalfountzos et al., 2007; Dougherty, et al., 2010).

Surprisingly, during this first period of the study, surface-sidedressing of fertilizer out yielded all fertigated treatments in two seasons (2007, 2008). Only in the first year (2006), a dry season, did fertigated treatments significantly increase cotton yield over surface-applied fertilizer. Since this study was conducted under rainfed conditions and as outlined earlier, the amount and distribution of rainfall are likely to have contributed largely to the lack of response to fertigation (Dougherty, et al., 2010). Delivering of surface-applied nutrients to the roots or leaching of fertigated nutrients away from the roots by rains or irrigations are possible too. The inability of roots to reach the fertigated nutrients at the drip line depth due to a soil hard pan could also be another reason. Comparing these results with previous and current research in this area, it is noted that the lack of response to fertigation observed herein contradicts the results of Janat and Somi (2001a, b), Janat (2004), Enciso-Medina et al. (2007) and Thind et al. (2008) who found that fertigation increased seed cotton yield. However, the results of increased seed cotton yield due to surface-applied sidedress with irrigation are in line with Hunt et al. (1998) and Hou et al. (2007) who found that sidedressing of N using drip irrigation in a single application increased cotton yield compared with multiple split applications.

In two seasons, surface-sidedressing coupled with supplementary SDI and rains resulted in generally better nutrient uptake than fertigation, particularly with N and K and indirectly to some extent with Ca and Mg but not P. However, this nutrient enhancement had no clear bearing effect on cotton lint qualities. Coker et al. (2009) reported that cotton lint yield responded 40% of the time to soil-applied K for irrigated cotton rather than for rainfed cotton. Girma et al. (2007) reported that application of N, P and K had some effects on cotton lint yield due to largely N and P whereas N and K were likely to affect lint qualities. The enhanced N and K uptake by sidedressing observed in this study increased lint yield without clear consistent effect on fiber qualities.

Conclusions

Under conditions of this study, conventional fertilizer surface sidedressing under SDI system out performed fertigation in two seasons out of three. Fertigation significantly increased cotton yield over conventional fertilizer sidedressing in the first season. Surface sidedressing enhanced nutrients uptake better than fertigation. Neither surface sidedressing nor fertigation had direct effect on cotton lint qualities. The observed responses to SDI fertigation were directly related to the amount and distribution of rainfall during the seasons. This is a long-term study in which cotton response to these treatments will continue to be evaluated under a wide range of climatic conditions.

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Defining the Run Time Multiplier

By

R.D. von Bernuth and Brent Mecham

Introduction

Sprinkler or spray irrigation is probably the most widely accepted method of irrigation of turf grass areas, but due to the inherent non-uniformity of the application method it becomes necessary to overwater some portions of the turf in order to preserve the appearance and persistence desired in the turf. The question to be addressed revolves around how much to increase the irrigation to ensure adequate quality in the irrigated area.

Non-Uniformity

The non-uniformity of sprinkler irrigation is can be shown graphically by plotting the depth of water applied through an irrigation system. The following example was produced by four irrigation sprinklers, each with a perfect triangular distribution pattern on a grid with the sprinklers spaced 50% of wetted diameter by 70% of wetted diameter. This figure shows the relative depth to which the water would have infiltrated into the soil, so the greater depths are farther down.

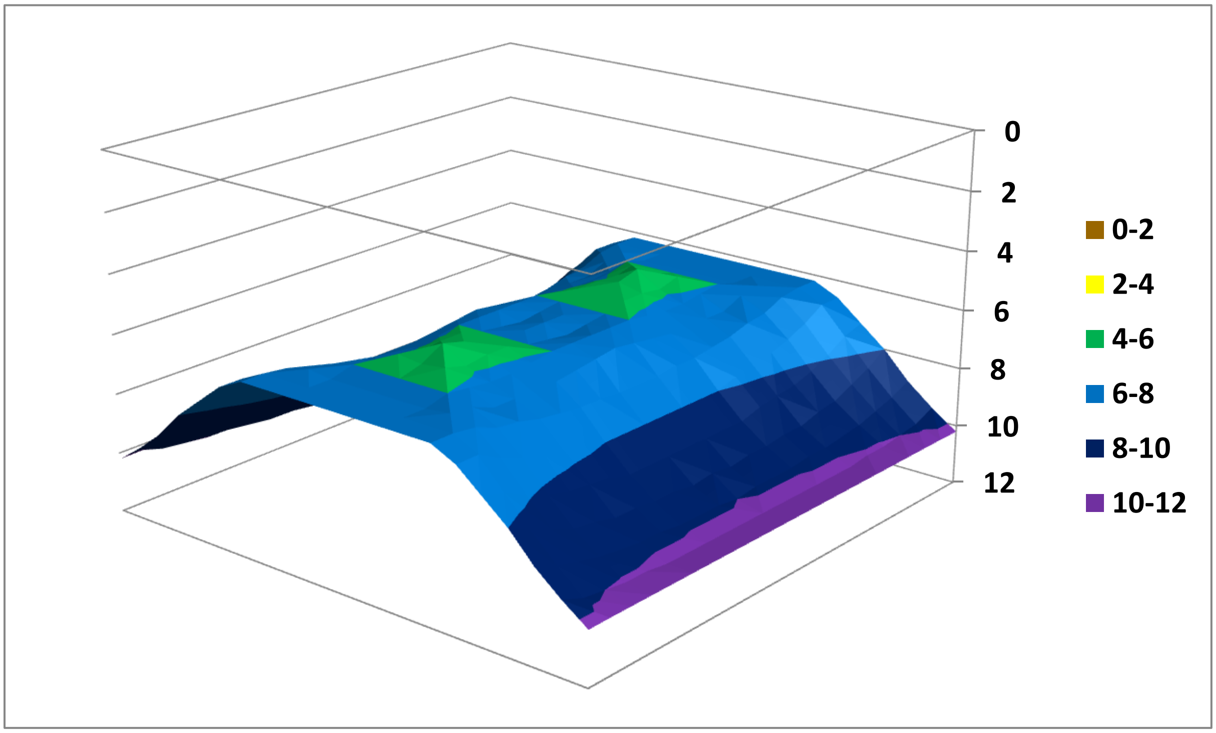

Figure 1. Overlapped Sprinkler Pattern, Example 1.

Along the edge where the sprinklers are spaced 50% of wetted diameter, the relative depth is exactly the same—10. Along the edge where the spacing is 70% of wetted diameter, the depth varies from 10 at the sprinkler to 6.2 in the overlapped area. Near the middle of the pattern, the lowest value (5.4) occurs in two spots. The average depth applied is 7.8. This system has a Christiansen's Coefficient of Uniformity of 0.805, a DU_{lh} of 0.810, and a DU_{lq} of 0.772.

There is a minimum value (depth) below which we are not willing to accept either due the appearance or decreased longevity of the turf. In order that all the area receives that minimum depth, we must run the system longer resulting in more water in some areas than needed. For the sake of discussion, let's assume that the average needed is 8.6. In order to achieve that number, we need to increase the time the system is run to by a factor of 8.6/7.8 = 1.10. Furthermore, if the average is 8.6, there is a level below which the depth is insufficient to achieve either the quality or longevity desired. For further discussion, let's assume that is 70% of the 8.6 or 6.0. The new plot of depth has the same shape and same location of minimum depth but has all the depths increased so that a very, very small spot has less than 6.0 as indicated by the tiny green spots. These two tiny spots (which are actually 5.94) represent 0.45 % of the area.

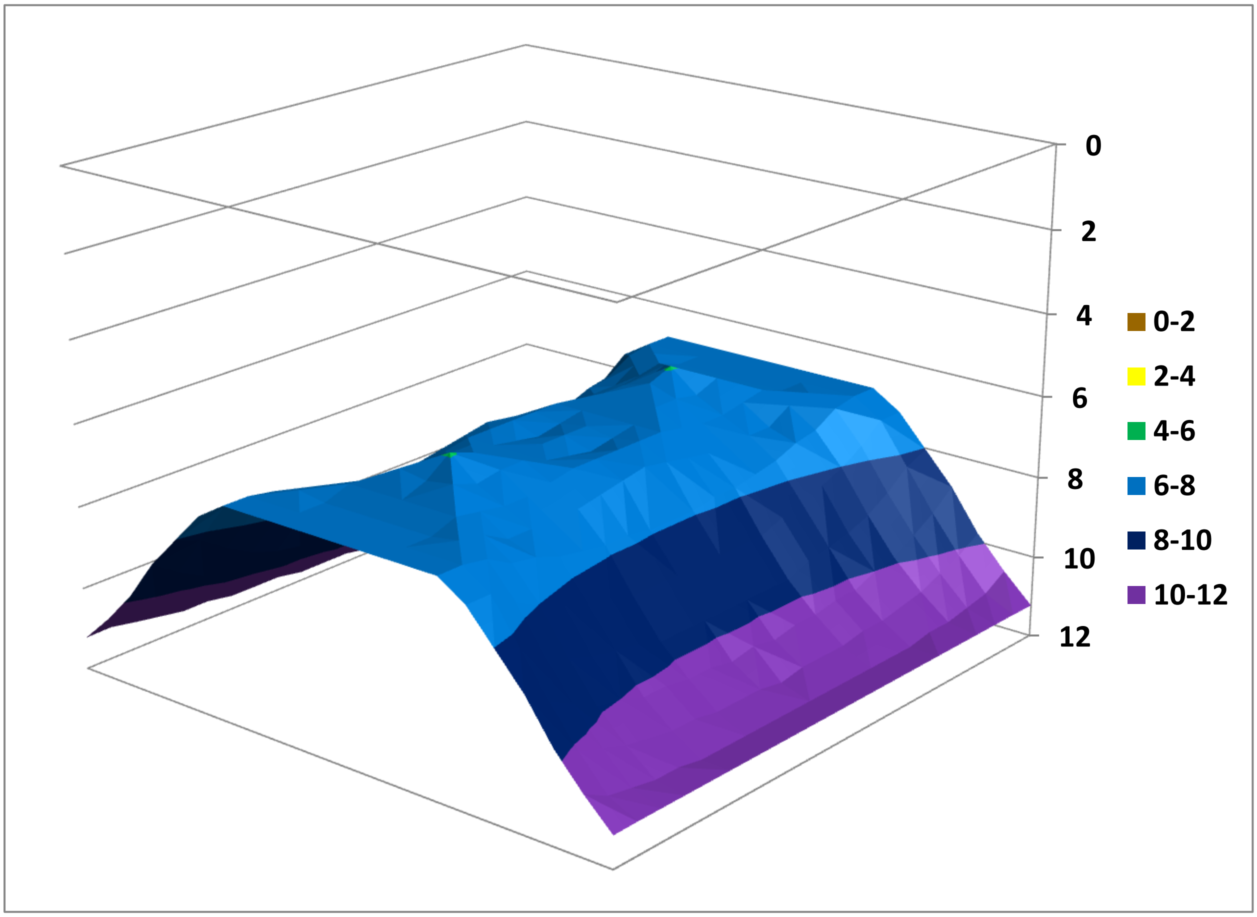

Figure 2. Overlapped Sprinkler Pattern, Example 2. 10% additional run time.

Two decisions have been made regarding this irrigation system. First, it was decided to run it longer in order to raise the average amount (and the minimum amount) and that anything below a given amount (6.0) was unacceptable. One more small correction will is necessary to meet the minimum acceptable amount by running the system 11.1% longer instead of 10% longer. The new average is 8.68, and the minimum is 6.00. The CU and DU's do not change.

Run Time Multiplier(s)

The Run Time Multiplier [RTM] as presented in several places in the Irrigation Association literature is based upon various methods of evaluating sprinkler performance. "*A run time multiplier is used to help compensate for the lack of perfect uniformity in sprinkler systems…RTM's are derived from the various methods of evaluating irrigation uniformity.*" (Irrigation Association, 2002.)

The idea of RTM was to communicate to the practitioner how much extra water should be applied based upon the lack of uniformity of the sprinkler system. In the auditing program, which is based on the original program developed in California, the plant water requirement was divided by the low-quarter distribution uniformity to determine irrigation water requirement. The RTM based on DU_{lq} is the same equation as determined by the irrigation water requirement (IWR) if the plant water need was one.

$$IWR = PWR / DU_{lq}$$

$$RTM_{lq} = 1/ DU_{lq} \tag{1}$$

In this example, if the plant water requirement is 1 and the DU_{lq} is 0.772 the irrigation water requirement is 1.30 inches. The practitioner would calculate that 30 percent more water would be needed, and would then increase the run time by 30%. By creating a RTM based on low-quarter distribution uniformity the practitioner sees immediately that 30 percent more water would be added or 30 percent more run time would be programmed compared to the ideal run time based on a perfect system. If the ideal run time were to be 20 minutes he would use the RTM of 1.30 to calculate a run time for the station of 26 minutes (20 minutes x 1.30 = 26 minutes). The system in the example run 30% longer as suggested by the RTM would have a minimum value of 7.0 and an average of 10.16.

If the run time multiplier is based upon Christiansen's Coefficient of Uniformity (CU_c) or DU_{lh}, then the amount of water applied would be different even though the information for CU came from the same data the was used to calculate DU_{lq}. Again referring to the example, the CU is 0.805 so the RTM can be calculated by equation 1 as

$$RTM_{lh} = 1/ DU_{lh} \approx 1/ CU_c.$$

If this is the case then the RTM would be 1.24 or 24 percent more water would need to be added. This is less water than a RTM based upon DU_{lq} but would it be a sufficient amount of extra water?

The Scheduling Coefficient is treated slightly differently in the IA Landscape Irrigation Auditor text (IA, 2007). "*The scheduling coefficient is a measurement of irrigation uniformity in an area that was* *developed for turfgrass irrigation. It is based on the critical turf area because in turfgrass irrigation it is common to irrigate any critical area until it is sufficiently watered. The SC indicates the amount of additional water needed to adequately irrigate the critical area. In the purest form, scheduling coefficient is based upon the absolute lowest precipitation rate versus the average precipitation rate. The critical area is typically defined as a percent of the total area (1%, 5% or 10%)*". The text goes on to explain that "*the difference between SC and DU is the fact that SC uses a contiguous area in defining the dry spot area to be used in establishing design and operational parameters*." Common practice is to use a"window "or contiguous area that is equal to five percent of the total area. In order to get a representative can test, a large number of catch cans would be necessary, and it just isn't practical to perform such test. However, computer simulations such as the one shown or densograms from SpacePro (CIT, 2009) are good examples.

It has been said that the SC could be used as a run time multiplier. Using the previous example, the SC would be 1.30, leading to a RTM of 1.30 and resulting in 95% of the area being overwatered.

Which RTM should be used? Vastly different amounts of water could be applied, all based upon sprinkler performance but measured by different parameters—DU, CU or SC. It is time to define which run time multiplier makes the most sense. Additional water is needed to compensate for the lack of perfect uniformity, but the efficient use of water resources is part of the IA's stewardship and mission statement.

Destination Diagrams

The authors believe that the best way to understand uniformity and management of sprinkler systems is by using destination diagrams. A destination diagram is a plot of the depth applied by a sprinkler system against the area. By plotting the line representing the depth against the area receiving at least that much water, a diagram such as shown below is produced. Figure 3 is the destination diagram for the system shown and operated as in Figure 1.

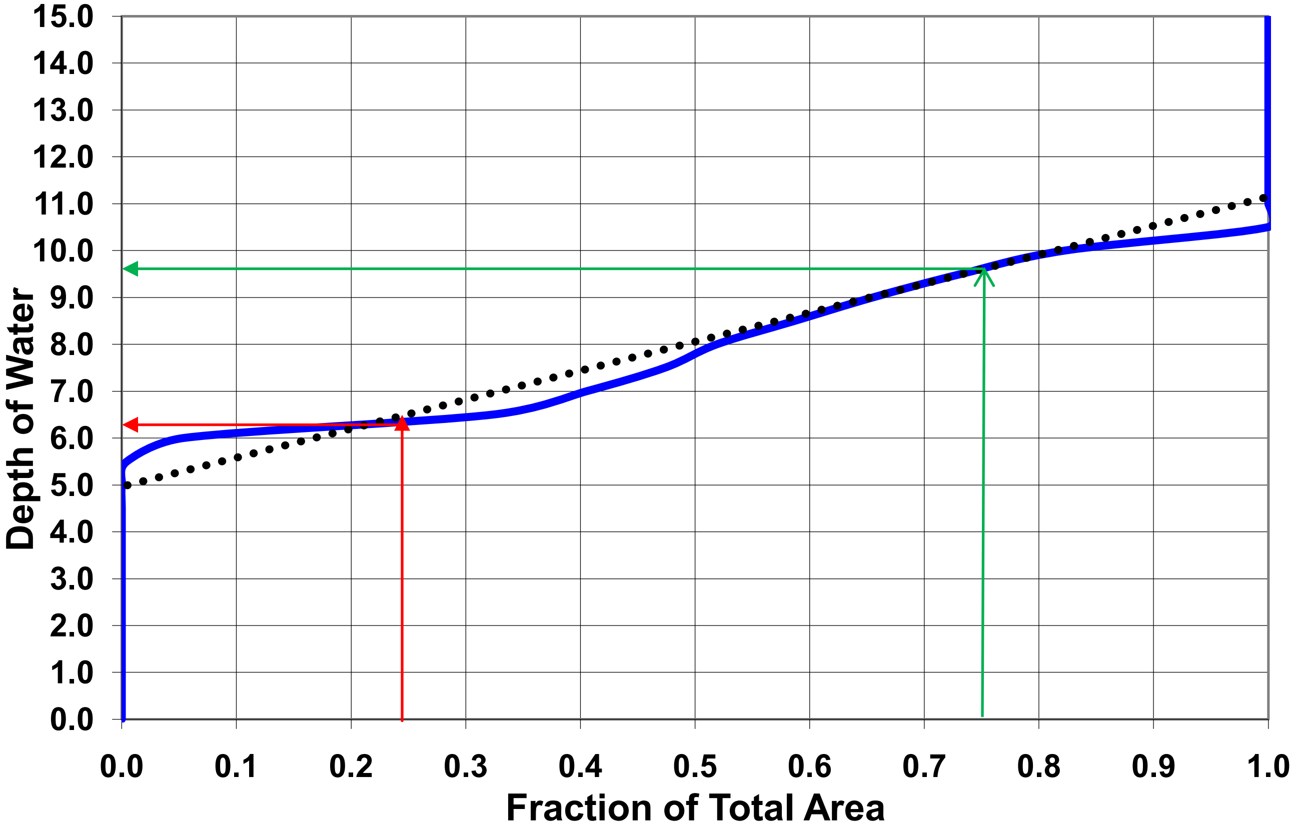

Figure 3. Destination Diagram for Example 1.

The actual line produced from the overlapped data is shown as the blue line, and the dotted black line is a straight line approximation. The destination diagram is interpreted as follows: by choosing a value on the y axis and following it to the line and then to the x axis, we see how much of the area receives a given amount. For example, we see that 50% of the area receives 7.8 or more. Similarly, 75% of the area receives 9.5 or less (green arrows). That can also be interpreted that 25% of the area receives 9.5 or more. We are mostly interested in the lower end, and we see that 25% of the area receives 6.2 or less (75% receives 6.2 or more[red arrows]).

If we used the RTM based upon DU_{lq}, we would have increased the irrigation amount by 30% (RTM = 1/ DU_{lq} = 1/0.772 = 1.30). The resulting values would have been: average=10.1, high = 13.2, and low = 7.0.

Two important questions arise from this discussion. 1. At what fraction of the average application (presumably based upon ET) defines critical? 2. What is the appropriate fraction of area to deem critical as referred to in the SC explanation above?

<u>Critical Application Amount</u>

There is a body of literature representing the research to indicate that most turfgrass irrigated to 70-80% of grass-based ET is enough to meet the goals of appearance and longevity. Aronson, et. al.

(1987) suggest that 80% of ET is adequate. DaCosta and Huang (2006) concluded that 60 to 80% of ET measured in a lysimeter was adequate for bentgrass. Bastug and Buyuktas (2003) concluded that 75% of class A pan evaporation was adequate for the conditions they tested in a Mediterranean climate in Turkey. McCready, et.al. (2009) found that water use could be reduced 11 to 53% without quality degradation on St. Augustine grass. The literature review presented by Bastug and Buyuktas (2003) shows a range of acceptable values from 50% to 130%, but the dominance of the values are between 70% for warm season grasses and 80% for cool season grasses.

Critical Application Area

What percentage of the area receiving less than the critical amount should we be concerned with? As the IA literature states, it depends upon whether the area is contiguous. The authors would argue that large portions of contiguous area are likely due to system malfunction and solvable as opposed to systematic and distributed areas due to spacing and sprinkler distribution profiles. If we agree that 70% is a number we can accept for the critical application amount, we should revisit example 1. As shown in Figure 1, the percentage of the area receiving less than 6.0 is 5.4%. With the pattern as shown in Figure 1, it likely is noticeable. However, a mere 10% increase in run time essentially eliminates the critical area. So, with this system with a CU of 0.805, a DU_{lh} of 0.810, and a DU_{lq} of 0.772, 10% increase is enough.

One could argue that the system in example 1 wasn't properly managed to begin with, and that the average should not be based upon ET but some fraction of ET thereby lowering the critical application amount. For example, if the average was based on 80% of ET, then the critical application amount to meet 70% of ET would be 0.875. (0.8 x 0.875 = 0.70). If that is the case, then the system under discussion would be run to give an average of 8.0 (2% more). Pursuant to that premise, the maximum would be 10.4 and the minimum would be 5.5. The area receiving less than 6.0 is a mere 4.5% of the total distributed in the same two locations as shown in Figure 1. Maybe the assumption that 6.0 is adequate just doesn't apply enough water. What would be the results if we used 80% rather than 70% resulting in 6.4 being adequate? What impact does that have on the result? With an average of 8.0 in example 1, 29.7% of the area receives less than 6.4. We could probably agree that isn't acceptable. In order to reduce the critical area to 10%, we would have to run 6% longer, and to reduce the critical area to 5% we would have to run 9% longer.

Our argument is that a run time multiplier based upon DU_{lq} results in much more water being applied than is necessary. In fact, a run time multiplier based upon DU_{lh} results in excess application. While we can't say exactly what the perfect way is to determine the RTM we believe it would be best to base it on no more than DU_{lh} . Furthermore, it makes sense to limit the RTM to a maximum value. For the practitioner the RTM helps define the upper limit of water to be applied and gives the manager guidelines for irrigation scheduling.

Maximum Value of RTM

Allen and Howell developed a method based upon the assumption of a normal distribution of water depths. It was published in document entitled Landscape Irrigation Scheduling and Water Management (2005) where they suggested a run time multiplier derived by equation 2 as follows.

$$RTM = \frac{1}{(0.4)+(0.6)DU_{lq}} \quad [1] \qquad (2)$$

Shown in Appendix B is the derivation of a similar equation for the scheduling coefficient based upon the assumption that the destination diagram is linear. It is shown below as equation 3.

$$RTM = \frac{1}{\left(\frac{1}{3}\right)+\left(\frac{2}{3}\right)DU_{lq}} \qquad (3)$$

Both of these equations limit the extra run time or water that would be applied. Without the cap included in the RTM, very poor performing systems with a low DU_{lq} would likewise have a very low DU_{lh} and would require excessive amount of water. Equation 2 limits the value to 2.5 whereas equation 3 limits the value to 3.0. Both are based upon $DU_{lq.}$ Nonetheless, these two equations, based upon the distribution patterns and resulting destination diagrams lead to RTM's with maximum values. As opposed to current teaching where poor uniformity gets increasingly more water, with the cap created in the RTM poor performing systems are not rewarded with excessive water. As a practical matter, poor performing systems even with additional water will show stress areas. The solution is to fix the sprinkler system and not just add additional water because it is perceived as easiest and cheapest way. As shown in the chart below, significant amounts of water can be saved compared to old teachings. Run time multiplier is a practical and defensible way to determine the upper amount of water required to adequately manage turfgrass in the landscape. A comparison of the methods presented is shown below in Table 1.

Conclusions

We believe that the current method of determining irrigation water requirement by dividing plant water requirements by DUlq leads to excessive water application. In the spirit of the IA's mission statement to promote efficient irrigation, the RTM presented in the Landscape Irrigation Scheduling and Water Management document and taught in Golf Irrigation Auditor should become the current and relevant teaching and practice to determine the upper limit of irrigation water to be applied to the turfgrass within the landscape. The destination diagrams and graphics validate the logic and reasoning behind the RTM. We further believe that there is room for more improvement, but further improvement depends upon fully understanding both the critical application amount and the critical application area.

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[1] This equation appears in the IA publication (2004) entitled Golf Irrigation Auditor. It was derived from an equation presented in Landscape Irrigation Scheduling and Water Management (2005) document under review. A discussion of how it could be derived is in Appendix A.

Table 1. Scheduling Parameters Derived by Three Methods

Du_{lq}	IWR (PWR/DUlq)	Linear distribution	RTM based on normal distribution
0.30	3.33	1.88	1.72
0.35	2.85	1.77	1.64
0.40	2.50	1.67	1.56
0.45	2.22	1.58	1.49
0.50	2.00	1.50	1.43
0.55	1.82	1.43	1.37
0.60	1.67	1.36	1.32
0.65	1.54	1.30	1.27
0.70	1.43	1.25	1.22
0.75	1.33	1.20	1.18
0.80	1.25	1.15	1.14
0.85	1.18	1.11	1.10
0.90	1.11	1.07	1.06
0.95	1.05	1.03	1.03
1.00	1.00	1.00	1.00

Appendix A

A relationship between the DU_{LH} and DU_{lq} based upon the assumption that the depths are normally distributed can be developed in the following manner. The normal distribution assumption makes the Christiansen's Coefficient of Uniformity (CU_c) equal to the DU_{lh}. CU_c is given by the following equation expressed in terms of the standard deviation and mean of the population.

$$DU_{lh} = CU_c = 1 - \sqrt{\frac{2}{\pi}}\left(\frac{\sigma}{\mu}\right)$$

Where σ is the population standard deviation and
μ is the population mean.

This allows the determination of the standard deviation given the DUlh. Therefore, σ is given by the following equation. The mean, μ, is set to one.

$$\sigma = \sqrt{\frac{\pi}{2}}\,(1 - DU_{lh})$$

It is straightforward to determine the mean of the low quarter of values once the standard deviation and mean have been determined. This sets the relationship between $DU_{lh} = CU_c$ and $DU_{lq.}$ The only problem with the relationship is that DU_{lh} values less than 0.70 lead to negative values in the lower quarter. That, of course, is impossible, so it is necessary to truncate the distribution and limit it to non-zero values. When all values are preserved (including negative), or DU_{lh} is limited to values greater than about 0.70, the relationship is linear and is as follows.

$$DU_{lh} = 0.6537 + 0.3463\ DU_{lq}.$$

For a range of values below $DU_{lh} = 0.70$ and with negative values in the lower quarter set to zero, a range of coefficients for the equation above results, and the correlation is no longer perfectly linear. It is this analysis that leads to slightly differing coefficients. For example, the draft for review of the Landscape Irrigation Scheduling and Water Management shows the values to be 0.614 and 0.386 respectively.

Appendix B

Development of the run time multiplier

The run time multiplier or scheduling coefficient is the amount by which to multiply the run time in order to assure that the area receiving inadequate water is minimized. If we use $1/DU_{lq} = RTM_{lq}$ as the multiplier, we assure that 87.5% of the area receives adequate irrigation. RTM_{lq} makes the average application equal to the average of the low quarter. That is represented by the purple line in the graphic below. Following the purple line intersection with the destination diagram line vertically to the scale, we see that 87.5% of the area receives adequate or more. On the other hand, if we make use $1/DU_{lh} = RTM_{lh}$ as the multiplier, the green line points to the area receiving adequate or more, and that is 75%. Many people are used to using DU_{lq} as the measure of uniformity, so the question comes up as to what the relationship is between RTM_{lh} and DU_{lq} . The sequence below shows how that relationship is developed.

$$DU_{lh} = Average\ \ lh\ values/Average$$

$$Average = v$$

$$Average = 1$$

$$Average\ lh\ values = d$$

Therefore, we have

$$DU_{lh} = d$$

Looking at the lower quarter,

$$Average\ lq\ values = q$$

The average of the low quarter values will be the average height of the trapezoid in the lower quarter. It has height of d minus one half of v minus d, so

$$q = d - \left(\frac{v-d}{2}\right) = \left(\frac{3d-v}{2}\right)$$

$$DU_{lq} = \frac{q}{v}$$

$$DU_{lq} = \left(\frac{\frac{3d-v}{2}}{v}\right)$$

However, we set v equal to 1, so

$$DU_{lq} = \left(\frac{3d-1}{2}\right)$$

We define the RTM as v/d, so

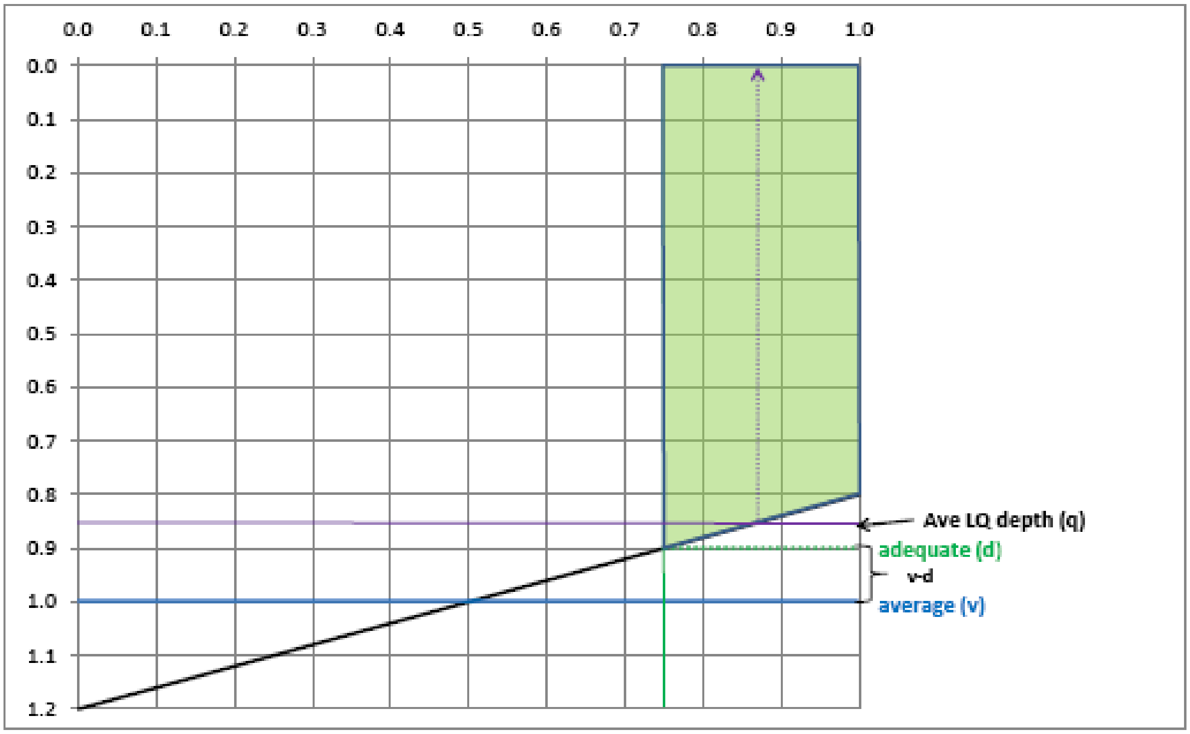
$$d = \frac{1}{RTM}$$

Substituting

$$DU_{lq} = \frac{\frac{3}{RTM} - 1}{2}$$

By a little math manipulation,

$$RTM = \frac{1}{\left(\frac{1}{3}\right) + \left(\frac{2}{3}\right) DU_{lq}}$$



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The Role of the Landscape Contractor to Conserve Water

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Abstract

Opportunities abound for property owners and managers to respond to challenging economic conditions by proactively deploying smart landscape services. Community boards and property managers increasingly seek landscape services partners who drive value and serve as a maintenance strategist rather than a vendor. It is critical in today's budget sensitive environment to count on a team of landscape experts who are aligned with your objectives and help maximize value on your property.

Some of the key points of this paper include:

- Why a landscape services partner is the best ally in helping customers reduce water usage and water costs
- Knowing why a water savings recommendation makes sense from both a financial and landscape best practice
- Identifying the collateral benefits that impact the total cost of ownership from implementing a water conservation program

An integrated landscape management program is the cornerstone for producing landscapes that help reduce the ecological footprint of a property. This management approach focuses on best management practices that include developing a water conservation program, irrigation efficiency, soil stabilization, plant health, and waste reduction while minimizing environmental impact.

Key Words

Irrigation, rebates, drought, landscape, turf, conversion, water management, water shortage, repairs, annual beds, controller, water budget, audit

How can you be an ally for property owners who are trying to be more environmentally-friendly and efficient with their water?

One area of potential high impact and significant ROI is a landscape plan that is grounded in efficiency and sustainability and is aesthetically polished. A key component of a smart landscape is water conservation. For owners and managers in arid regions, it is a fact of life. But for some, water may not be perceived as a precious resource simply because it seems to be plentiful in the area in which they operate. Even though water is relatively inexpensive, it is a limited natural resource. Adopting a smart water management program now is a critical component to operating a commercial site at peak efficiency at all times, not just when drought conditions or irrigation restrictions exist.

Forward-thinking companies are already implementing sustainable landscaping practices in an effort to reduce operating costs, minimize the environmental impact of their property, and improve their return on landscape dollars invested. They are turning to their landscape partners who are knowledgeable about irrigation which is often a major concern, both to manage and to budget for the expense of repair and upgrades.

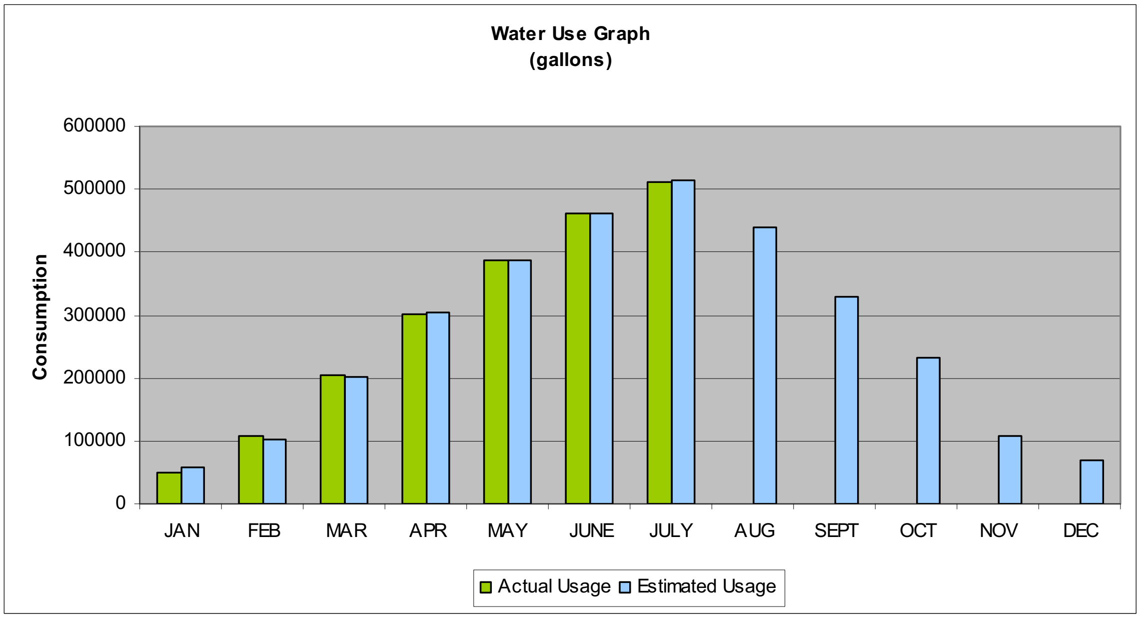
Grounds managers should get involved in the landscape design and planning process to avoid landscapes that are costly and difficult to maintain. Any landscape undergoing extensive rework typically involves designers who know what looks good, but may not consider long term maintenance requirements. Bringing the maintenance team in early in the process helps maximize potential growth for landscape, while minimizing cost and environmental impact.

What are the priorities?

By proactively deploying smart landscape services, property managers can reduce landscape costs, while still improving the sustainable elements of a property. Applying some simple measures and best practices can provide cost-savings and other benefits. The impact of a smart landscape and maintenance plan can be significant, as we've seen annual savings in the 15% to 20% range. When making decisions about how to achieve your customer's goals, an obvious starting point is to assess the existing design, irrigation system and planting materials before developing a plan to improve and enhance a property.

Properties constructed 20 or more years ago have common age-related elements that typically need to be addressed. First look at the irrigation system, which usually involves deploying more advanced technology. Smart controllers or sensors to detect when plants actually need water didn't exist when properties were built in the 1970s or 1980s. By investing in these kinds of improvements to an irrigation system, a property can generate the kind of savings that would expect to pay off within 24 months. We're seeing even shorter ROI periods, as property managers and their landscape partners continue to refine and respond to the need to drive immediate results in the current economic climate, while incorporating more sustainable practices such as turf conversations and drought-tolerant plant materials.

At one property just outside of Las Vegas, better irrigation practices contributed to a more efficient and cost effective landscape, not to mention a happier, more satisfied community. By upgrading the irrigation system, the water needs of each zone within the site could be better served. ValleyCrest installed six ET-based controllers that provide weather data to automatically adjust the irrigation. They also assessed the various zones on the property to determine irrigation needs based on plant requirements in each area. High-efficiency parts such as matched precipitation sprinklers and rotary nozzles also helped apply water to the landscape as efficiently as possible. In addition, about 20,000 square feet of turf was converted to native landscape with SNWA rebate covering the cost.



Sustainable landscape is good for the environment and can impact bottom lines as well. Replacing existing plants with native or drought resistant plants will help address a need for all to use water resources more wisely, even if a property is able to utilize a recycled water source or if one believes they are in a region where water is plentiful. As part of your evaluation, consider doing an irrigation site audit to identify potential water wasting practices and make the case for improvements on your customers' properties. For example, some of the areas to consider include:

1. Are there non-functional turf areas that are difficult to mow or irrigate that should be considered for conversion to other plant material such as shrubs?
2. Are stations properly hydrozoned or are some plants within certain zones being watered excessively?
3. Do any rotor nozzles need to be replaced to matched precipitation rates and desirable flow rates? 1/4's to 1/2's to Fulls?
4. Can spray nozzles be converted to MP Rotators? Is the water window long enough to use low application nozzles?
5. Is there a deficiency in pressure that prevents us from running multiple controllers, programs or valves simultaneously?
6. Can the existing irrigation system support a conversion to ET based controllers?
7. Would rain or wind sensors be beneficial? Do we shut all controllers off after rainfall or during periods of high winds?
8. Would moisture sensors be beneficial? Are there soils or areas that have poor drainage and are constantly wet?
9. Does the property have frequent mainline breaks? Should we propose installation of master valves, flow meters and isolation valves?
10. Is a full system or selective zone catch can test recommended?

Conclusion

Since you already have an established line of communication with your customer and are knowledgeable about water management, you can build on that trusted relationship by offering additional suggestions to help them maximize their landscape investment while minimizing costs. To determine the best water conservation strategies for property owners and managers, be sure to collaborate with building management, water agencies, and irrigation equipment manufacturers.

As experts in the irrigation industry, we need to lead the change in consumer mindset that water is an unlimited resource where indiscriminate waste is overlooked. While it is good to have best practices documented, they are little more than words if we don't put the actions into play.

You as the trusted landscape partner can offer recommendations such as the following that demonstrate your expertise and help your customers achieve their environmental and financial objectives.

- Analyze water usage trends and develop a water management plan to ensure irrigation systems operate efficiently, irrigation runoff is reduced and reclaimed water is used. Establish baseline usage and estimated water budget. Track usage before and after upgrades.

- Perform a site audit.

- Switch from overhead irrigation to a more efficient drip system; install smart weather-based controllers to measure precipitation, solar radiation and wind; adjust automatic systems, and look for ways to incorporate reclaimed water.

- Practice hydrozoning or grouping plants with similar water requirements on the same irrigation valve to reduce over-watering.

- Implement a rotation schedule for water features so fewer operate at one time, reducing energy costs.

- Retrofit your landscape with sustainable, water-efficient landscapes and native, drought-tolerant plant materials to reduce the use of natural resources and decrease the amount of maintenance required.

- Develop a long-term program that promotes a more water–efficient landscape.

- Maintain landscapes that are in harmony with the environment by reducing green waste, nurturing healthy soils, and reducing storm water runoff.

- Install flowering perennial plants to provide a sustainable and cost-effective replacement for seasonal color changes.

- Optimize the placement and health of trees around your buildings to increase shade and reduce energy costs.

- Maintain the landscape naturally by using pruning techniques that highlight the individuality of each plant.

- Explore public programs and grants offered by water districts, cities, or other entities that provide rebates or credits for upgrades on controllers, efficient irrigation, drip conversions, or rain shut-off sensors.

Richard Restuccia guides community boards and property managers through a strategic process that can result in reductions in landscape irrigation costs. Richard is the Sales Leader for ValleyCrest Landscape Maintenance for the Western United States. He has been associated with the Green Industry for over ten years working for ValleyCrest Companies and Rain Bird Corporation. Richard is currently working with Business Developers at ValleyCrest to help teach customers the advantages of proper water management. He helped organize a central control users group in Kern County whose goal was to reduce water consumption in landscape irrigation. He received his M.S. in Agribusiness Management from Arizona State University. He serves on the San Diego Water Conservation Action Committee. Richard consults with many private companies and public agencies concerning water management.

Irrigation Efficiency Management And LEED Certification

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We are discussing LEED Certification and some of the steps clients utilize in the LEED Certification application process. We are also exploring our role as Licensed Irrigators related to LEED Certification.

During a recent interview, Johnny Madison, a 40 year Veteran in the Irrigation Industry stated:

"I am familiar with LEED. It is a good program with great potential for water conservation. The only drawback to the program is the lack of awareness and understanding of the program and what it can do. I feel there is a future for the Irrigation Industry in LEED Certification, if the contractors, owners and developers will get on board."

The Irrigation Industry, like most industries, uses abbreviations and acronyms. Some of our more common ones are DU (Distribution Uniformity), ET (Evapotransporation), MP (Matched Precipitation) and VAN (the Variable Adjustable Nozzle) just to name a few. We are comfortable with them.

Let's step out of our comfort zone to recognize a few new ones that most of us have not used yet.

First, the USGBC, the letters stand for the United States Green Building Council, a third party organization that provides education, training and establishes the standards for LEED Certification

Now let's look at the actual acronym LEED, which is the abbreviation for Leadership in Energy and Environmental Design, is a process of reporting, inspection and review of a building to implement a plan for ensuring high performance. LEED involves a rating system for the certification of many facets of a facility.

Also of equal importance and easy to confuse with the USGBC is the GBCI. They are the Green Building Certification Institute, which is recognized as the leading third party agency for testing and training of individuals that achieve credentials in the LEED process, such as a Green Associate or a LEED AP.

There are credits available in new construction; there are also credits available for existing buildings, under application for certification.

LEED Certification starts when your client builds a design team and begins an application process. There is a measurable set of credits for many facets of the facility. Goals are set to achieve these credits within a point system. At this point an initial scorecard can be created. There are credits available for irrigation efficiency and for reduction in use of potable water for irrigation.

We can be instrumental in documenting the system capabilities. Is their system metered or sub metered? What are their velocity flows and pressure readings? What have been the actual run times? We help establish the data to be used as a baseline.

Next, we play a vital role assisting the architect and the manager as they review the methods for possible reduction of water use. We provide expertise regarding drip irrigation, smart controllers and Irrigation Efficiency Management. We step up And perform the needed irrigation audits. When the application process is underway, we are needed to help keep the records of the monthly monitoring.

We will need to break some old habits and become more attentive to loss of water on sites. We will need to increase the detail within our proposals and provide more documentation on each project that we service.

During an interview with Mike Cocayne, another industry veteran, Mike stated:

"The biggest change over the past few years is people starting to understand water conservation. The people in the industry that continue to keep making these types of changes are the ones that will make it"

As we begin to evaluate irrigation systems for the LEED credits, we will learn to refine our client's goals and research deeper into the shortcomings of each particular irrigation system. We will increase our understanding of budget considerations and have the opportunity to qualify the client's level of commitment.

There is a lot of information currently about ET Management, sustainability and reduced use. Do your own research and clearly define each individual clients water management needs. Let's be careful not to use a blanket approach and thoroughly discern the client's needs and the most logical approach to their individual property.

In the words of Abraham Lincoln:

"Better to remain silent and thought a fool, than to speak out and remove all doubt"

Some of the changes we will incur through our commitment to LEED will be going paperless; realizing depth through our organization with recycling and site documentation. We will learn to provide submittals and create audits with cover letters that contain our Irrigation Seal. We will electronically provide (web based) access to irrigation reports, cut sheets and specifications records.

The Opportunities are unprecedented. We get to strengthen our relationships with clients, engineers and architects while providing additional service and support. At the same time we will provide the modifications, the smart controllers and the drip irrigation.

Let's recap.

The USGBC is growing and LEED is a thriving certification process. There is an important arena involving irrigation. We can play a vital role. Sales opportunities do exist and the future of this industry does mean change.

Let's team up and embrace this unprecedented evolution…

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Microirrigation for Sustainable Water Use: Research and Outreach through a Multi-State Collaboration

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ABSTRACT. *This paper summarizes recent developments, ongoing efforts and planned activities of a long-term research and outreach collaboration to advance microirrigation. Participation of research and extension programs from 15 universities and 2 federal agencies from across the United States, including Puerto Rico and the Virgin Islands, makes this a truly regional endeavor. Since its inception in 1972, this USDA-RRF Regional Microirrigation Project group has been very active, with members participating in organizing conferences, writing microirrigation books and contributing many papers at conferences. Integrated applied research and outreach education objectives emphasize practical applications and delivery of information for end-users. Building upon past efforts, including recent work to improve understanding and remove barriers to adoption of microirrigation technologies, the group is developing recommendations and best management practices for successful implementation and sustainable application of microirrigation.*

Keywords. Microirrigation, subsurface drip irrigation, evapotranspiration, irrigation scheduling, irrigation research

INTRODUCTION

Through multi-state, multi-agency and interdisciplinary collaborations under the guidance of the United States Department of Agriculture National Institute of Food and Agriculture (NIFA, formerly the Cooperative State Research, Education, and Extension Service, or "CSREES"), regional project research teams work to solve problems identified as critical public concerns. Regional projects must have clear and focused objectives; direct involvement of multi-state and multi-disciplinary participants; approval through a peer-review process; direction toward achieving specific outcomes and impacts based upon stakeholder identified priorities; and they must be responsive to NIFA goals (USDA-NIFA, 2009).

The USDA-RRF Regional Microirrigation Project group has been working since its initiation in 1972 to address practical issues related to applications of microirrigation technology. Originally formulated as a western U.S. regional project concerning drip and trickle irrigation, W-128, the group has always included a multiple of disciplines such as irrigation engineers, crop and soil scientists, chemists and agricultural economists. The project was known as W-128 until 2004, when administrative requirements necessitated a name change to W-1128, which ran from October 2004 through September 2009. The goal from the original project inception has been to advance microirrigation as a potentially highly efficient irrigation technology by addressing technical concerns (system design and maintenance), application and management concerns (irrigation scheduling, chemigation, and crop-specific issues); and education and technical support concerns (information accessibility and outreach education). Applied research and targeted extension efforts conducted by participating Land Grant University and USDA-ARS programs are addressing specific identified needs.

A major project accomplishment during the early years was publication of the original reference book, *Trickle Irrigation for Crop Production: Design, Operation, and Management* (Nakayama and Bucks, 1986). Several current project members were involved in the completion of this book's revision, *Microirrigation for Crop Production* (Lamm, et al., 2007). *Microirrigation for Crop Production* summarizes the advancements made in design, operation, and management of microirrigation systems since *Trickle Irrigation for Crop Production* was published in 1986. Suitable as a comprehensive reference for researchers and practitioners or as a textbook for irrigation courses, *Microirrigation for Crop Production*, addresses microirrigation theory and design principles (including soil water concepts, irrigation scheduling, salinity management, general design principles applicable to all microirrigation systems, and economics of microirrigation); operation and maintenance principles (including system automation, application of chemicals, application of biological materials, field performance and evaluation, and system maintenance); and system type and management principles (including design, installation and management of surface drip, subsurface drip, bubbler and microsprinkler systems). The project participants have also been heavily involved in the International Microirrigation Congresses, particularly those held in the United States in 1985 and 1995. Numerous other technical manuals, Extension fact sheets, short courses, demonstrations, journal articles, field days, web sites and other products and programs have been developed to ensure that results from the research efforts are readily available for use by the public.

Building upon these accomplishments, the microirrigation research group has initiated the project for the next 5-year cycle, W-2128, “Microirrigation for Sustainable Water Use,” to address newly identified and lingering technical and practice issues related to applications of microirrigation technology. Objectives of this work will include: 1) comparing irrigation scheduling technologies and developing grower-appropriate scheduling products; 2) developing design, management and maintenance recommendations; 3) developing best management practices for application of agricultural chemicals; and 4) evaluating use of non-potable water through microirrigation.

Comparing irrigation scheduling technologies and developing grower-appropriate scheduling products

Although microirrigation is widely considered to be the most efficient irrigation method, additional water savings are achievable through refinements in microirrigation management. Improvements in irrigation scheduling (timing and amounts) can result in significant water savings, but water savings must be balanced against the economic necessity to maintain or improve crop yield and quality.

Several microirrigation scheduling approaches can be utilized for any particular crop and environment, and many practical factors, including irrigation system capabilities, should be considered. Methods used for on-farm irrigation scheduling are often based upon evapotranspiration (ET) estimates from locally available weather data; soil moisture management; and/or plant-based indicators. Evapotranspiration estimates apply understanding of overall plant water requirements and atmospheric water demand through a mass balance approach (Howell and Meron, 2007). In this approach, reference ET for a standard canopy is calculated from weather data and then multiplied by one or more crop coefficients (Kc) to estimate the water requirement for a particular crop. This approach is well established, yet continued research is needed to advance understanding of underlying factors and applicability of the method to additional crops and production conditions, particularly practices involving deficit irrigation, as well as to improve interpretation and application of ET information to microirrigation scheduling.

Soil moisture management based irrigation scheduling involves direct or indirect measurement of soil water, as well as an understanding of soil moisture storage capacity and irrigation system capacity. Research and informational materials are needed to support proficiency in selection and placement of soil moisture sensors and correct interpretation of soil sensor data. Plant indicator based irrigation scheduling may use direct or indirect measurements of plant water status to determine when water should be applied. Research and informational materials are needed to evaluate and promote appropriate plant water assessment technologies, and proficiency in applying them and in interpreting the information they provide.

In addition to improvements in assessing crop water demand for irrigation scheduling, information is needed from a range of crops and environments to determine the effects of different irrigation scheduling approaches on yield and product quality. Particularly in production systems where water resources are limiting, understanding of crop response to managed deficit irrigation strategies will be essential to optimizing limited irrigation water resources. While it is generally assumed that irrigation should fully meet ET-based crop water demand to maximize yield, economic and/or horticultural benefits of managed deficit irrigation (regulated deficit irrigation, RDI) have been demonstrated for some crops (Boland et al., 1993; Shackel et al., 2000). Research conducted under this project will investigate crop response to these regulated deficit irrigation and other strategies, intended to utilize more fully the flexibility and precision in water application afforded by well-planned microirrigation systems.

Soil moisture and plant indicator based irrigation scheduling methods using sensors and controls to initiate and terminate irrigation can also be readily applied with microirrigation, taking advantage of its high degree of automation and application uniformity. Major advances in sensor technology, including improved reliability and communication capabilities, have improved potential for utility of these tools in microirrigation. Sensor calibration and comparison, and evaluation of sensor-based controls and strategies will be conducted.

Developing design, management and maintenance recommendations

Another key to sustainable water use through microirrigation is the improvement of crop yields through improved microirrigation management and increased usage and reliability of microirrigation systems through better system design and maintenance. Interest in microirrigation technology is increasing in many areas, and adoption of microirrigation often involves comparison with other irrigation methods commonly used within a region. These system comparisons generally consider crop yield and economics, water use and conservation, and environmental issues (chemical leaching and drainage). Although the pertinent factors may differ with region, crop, soil, and climate constraints, proper management strategies for any irrigation method, particularly those methods with which producers are less familiar, such as microirrigation, must be developed or adapted for local conditions. This project aims to establish baseline information about alternative irrigation systems for various crop production systems and regions. Results will be shared among participants, and will be used to develop common guidelines for optimizing performance of the various irrigation systems, taking into account economic and environmental considerations.

Recent surveys conducted by the USDA-RRF Microirrigation Project group have indicated a need for continued and expanded research and extension efforts to help producers manage for optimal crop production, protect the environment, and maximize system life through proper maintenance. Emitter clogging remains the primary cause of microirrigation system failure, so improved emitter maintenance will be a key factor in having sustainable microirrigation systems. The project group will create a widely applicable web-based tool, compiling recommendations based upon diverse research efforts, to assist producers in assessing and addressing clogging hazards.

Developing best management practices for application of agricultural chemicals

Conjunctive use of agricultural chemicals with microirrigation can help achieve sustainable water use through greater crop yields and improved crop quality, and through protection of surface water and groundwater resources from agrochemical pollution in runoff and leachates. Agricultural chemicals, whether applied through the irrigation system or through other means, are used for a wide range of purposes. In maintenance of microirrigation systems, acids, chlorine, herbicides and other products are sometimes used to prevent emitter clogging due to chemical precipitates, biological growths, or root intrusion. Precise application of fertilizers and/or pesticides through the microirrigation system is often cited as an advantage of microirrigation (Ayars et al., 2007). Effective use of fertilizers or other agricultural chemicals applied through other means (ground rig or aerial application, for instance) may require extra considerations in microirrigated conditions. Potential obstacles to chemical applications with microirrigation include limitations to applicability of soil injected chemicals and limitations of agricultural chemical labeling for microirrigation application.

Microirrigation chemigation is based on the principles of precision farming where system inputs are qualitatively and quantitatively matched to the needs of the crop. Subsurface drip (SDI) and surface drip systems (DI) can be used for the injection of systemic pesticides and some biocontrol agents while surface microsprinklers may be used to apply biocontrol agents over larger areas and on plant canopies. Use of SDI systems for systemic insecticide or fungicide application has the advantage of compatibility with integrated pest management principles. However, the use of pesticides through microirrigation systems is much less advanced as compared to nutrient fertigation. Current research programs conducted by participants of this project are beginning to address fertigation and chemigation through microirrigation (particularly through subsurface drip irrigation), yet results are generally preliminary or otherwise not sufficiently interpreted for development of best management practices. Research and extension/outreach associated with this project will advance knowledge necessary to develop, evaluate and recommend best management practices.

Evaluating use of non-potable water through microirrigation

Sustainability of water use can be augmented through microirrigation of non-potable waters. Use of non-potable waters as an alternative water resource is becoming more common as limited high quality water sources are allocated to higher priority municipal and industrial users. Irrigators are increasingly turning to lower quality water sources, including saline surface water and groundwater and reclaimed water from wastewater treatment plants, animal agriculture operations, and other effluents and produced waters.

Extending the concept of sustainability to life of the system, microirrigation of non-potable waters requires careful selection of system components and appropriate management of the overall microirrigation system. Use of non-potable water can reduce treatment costs by reducing the level of treatment required for environmentally appropriate disposal. In fact, some non-potable waters contain nutrients that can be beneficially used to meet crop requirements. Yet there are often other concerns, including salts and potentially excessive levels of some constituents that require special management to avoid adverse impacts on soil quality and crop productivity. Nutrients and other constituents in these waters present additional challenges to operation and maintenance of microirrigation systems. Since non-potable waters can come from processing facilities, homes, municipal treatment plants, rural municipal lagoons, and livestock lagoons, the characteristics of these water sources can vary widely in terms of chemistry, biological activity, and physical condition. These characteristics influence filtration requirements, treatment practices, emitter performance, soil conditions, and crop and landscape performance. Through this project, research will be translated into better recommendations for system hardware selection, improved maintenance procedures and guidelines for non-potable water utilization for different geographic locations, environmental conditions, soil characteristics, and water sources.

SUMMARY

Sustainability and conservation of limited high quality water resources necessitate high irrigation application efficiency and overall water use efficiency. Preserving and protecting the quality of water resources includes safely using lower quality waters for irrigation and preserving high quality water for drinking and other uses. To justify investment in and adoption of microirrigation technology, economic sustainability must be addressed through maintaining crop yield and quality and by ensuring longevity of microirrigation systems.

Applied research programs at multiple locations will evaluate microirrigation scheduling strategies and products and develop recommendations for applicable tools according to crop, location and farm-level capabilities. Researchers will build upon previous research progress to address irrigation system design, management and maintenance concerns related to microirrigation system performance and longevity. Since microirrigation technology is well-suited to precise application of agricultural chemicals, team members will investigate products and protocols and develop best management practices for application of agricultural chemicals with microirrigation. Through studies using reclaimed and other non-potable water sources, researchers will assess the advantages, limitations and necessary precautions associated with beneficial use of lower quality waters. Resulting recommendations will be made easily accessible through user-friendly online trouble-shooting tools.

The aim of the project team is to promote adoption of microirrigation by developing practical solutions to concerns related to application of the technology. To maximize the impact of the research, educational materials and opportunities will be emphasized throughout the project. Research results, recommendations and best management

practices information will be made available to the public through audience targeted meetings, workshops, field days, print and electronic media (including public web sites).

The project participants from various universities, USDA-ARS and USDA-NRCS locations have a long history of working together cooperatively on the topic of microirrigation. Progress has been steady over the years since 1973, and current project members are excited about the potential for further expansion of microirrigation.

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University of Arizona	Muluneh Yitayew	Agricultural Engineering
University of California-Davis	Patrick Brown Jan W. Hopmans Larry Schwankl Kenneth A. Shackel	Pomology Vadose Zone Hydrology Irrigation Engineering Pomology
Colorado State University	Mike Bartolo	Plant Physiology – Vegetable Crops
University of Florida	Lawrence Parsons Bielinski M Santos Craig D Stanley	Horticulture Horticulture Soil and Water Management
University of Hawaii	Ali Fares	Watershed Hydrology and Tropical Soils
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Prelude to Change:
Defining Roles in Landscape Water Management

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Abstract

This presentation by US EPA Water Efficiency Leadership Award winner describes his vision for filling the missing link in landscape irrigation water management and sustaining our living landscapes with a newly evolving industry focused on water management. During a time when water was plentiful and price was cheap, very little attention was directed toward landscape irrigation. However, times have changed and the demand for professional consultants serving commercial real estate owners is now.

This new industry must be able to fulfill a comprehensive approach to water management including:

- Irrigation scheduling
- Modification of landscape cultural practices
- Elimination of potable water sources
- Proper planting plans for region

At a time when water utility providers look to any avenue of conservation, including turf and plant removal, this industries primary challenge will be sustaining irrigation water conservation and preserving landscapes significant long-term benefits to our environment and health.

Keywords

Comprehensive irrigation management
Water conservation
Preserving landscape
Environmental impact

Prelude to Change

Until recently, United States water policy and laws were derivative of a time of excess and plenty; however, in spite of our increasing awareness of the potential for water shortages, we continue to operate in denial of the reality of our threatened fresh water supply. Numerous regions in this country are faced with potable water shortages due to lasting effects of drought, increasing population, environmental and endangered species requiring protective measures, and a global shift in the climate.

Present day voters are showing progressive concern with environmental issues, while many recent judicial verdicts exhibit support of the environment, in-stream flows and endangered species over other water stakeholders. Watering restrictions and recommendations for the depletion of managed landscapes are to frequently touted as a valid solution to reducing water use. In order for our irrigated landscapes to survive this onslaught of pressure, we must rise to the challenge and become the best possible stewards of this precious resource we call water. As a concerned citizen and professional in the irrigation landscape industry, it is my core belief that landscape and irrigation professionals must unite with the common goal of protecting our landscapes through heightened stewardship of the water resources available to sustain them and our own human existence.

As pressure on our urban water supplies have continued to grow, water purveyors have often reacted with considerably short sited solutions with disregard for the long term environmental consequences. One example of recent is the turf removal program in the Las Vegas, Nevada area, where the water authority has paid $238 million to remove 5,500 acres of turf grass from the landscape over the last two and one-half years. Some of the areas were modified with hardscape, others with native plantings and high efficiency drip irrigation. While this program has its merits with encouraging use of native plants well adapted to the region's desert climate, the program has been touted as a success for reduction of water consumption, the latter which has only elusively quantified the actual water savings. Program skeptics point to a natural reduction by homeowners due to the current economic recession, coupled with an abundance of home foreclosures and vacant properties where no watering is occurring at all. Imagine the resulting measurable water savings in the same regional area if the $238 million dollars funded for turf removal were instead directed towards a program advocating restoration of outdated and broken irrigation systems, implementation of new irrigation technology, and enhancement of system and management efficiencies?

An Industry in Fluctuation

The landscape and irrigation industry has not prepared itself to deliver measurable, documentable data to support return on conservation investments for property owners, nor to support our conservation efforts to water authorities. For decades, commercial property owners have looked to the landscape and irrigation professions for expertise and advice on maintaining their landscape investments. In many instances, property owners and managers have designated the landscape service provider as the responsible party for managing the site's water by including irrigation water management in the scope of services for the general landscape maintenance package. This has resulted in a service that is devalued by awarding zero compensation and fostering little or no attention to the real issue of providing irrigation water in an efficient manner. Additionally, unaware of actual water costs and consumption, the service providers historically err to excessive water application, resulting in additional, unnecessary waste.

Because the landscape service business has become a commodity service, landscape and irrigation professions have been unable to sustain respect and trust of commercial property owners. To a large extent, the blame for excessive water use has landed squarely on the backs of these professions, while the real problem may actually rest on the manner in which business is conducted between the commercial property owner and the landscape service providers. By shear nature of the business and as a commodity service, landscape service contracts are constantly changing; i.e., landscape service providers come and go, but the site and its context remain. Water management of these sites must be able to survive this fluctuation between commodity service providers in order to effectively sustain measurable water savings and preserve our landscapes.

As a life time descendant of the landscape and irrigation industry, I harbored skepticism as to how effectively this change could be implemented and, whether it would truly make a difference. Since my departure from the commercial landscape service business in 1998, I have dedicated the last eleven years modeling a concept of professional water management that could successfully integrate with the existing service industry. Today, I come before the Irrigation Association membership to speak with you about redefining roles in landscape water management, sharing my experiences and to enlist your support and involvement in the formation of a professional landscape water management industry, quietly in the making.

An Industry in Formation

Over the past two years, having attended multiple water related conferences, dabbled in water policy and legislation and provided input to affiliates of water conservation programs and State and Federal levels, I have noted a common thread. There is an overwhelming theme of fragmentation and disconnect amplified by all stakeholders: water utilities demanding landscape professionals to step up conservation efforts; irrigation manufactures being asked to provide documentation supporting savings claims; landscape professionals asking, "How did I get delegated responsibility for watering?"; irrigation professionals assuming control of the water while historically blamed for overuse; regulatory agencies wanting to hold someone else, anyone else accountable; and finally, water utilities wielding the hatchet to restrict landscape watering, and blaming new landscape installations and plants for excessive water use. Complete chaos – division and continued internal and external fragmentation amongst all stakeholders.

Sorting through all the noise generated within the water stakeholder groups, it is apparent there is a missing component in the landscape water management arena of responsibility. My vision has been to create a new industry focused on water management and capable of bonding the stakeholder parties through trust and respect. In early 2001, my partners and I formed a performance based water management pilot project to prove the theory that 20 percent of landscape water could be saved simply by focusing on precision application. After seven years, the company has documented over 64.8 percent in savings across a seven state portfolio of commercial properties. By managing rain events, monitoring flows, reporting leaks and system inefficiencies, and with precise application based on range-based soil moisture management, these savings equate to greater than 1.5 billion gallons of water. Just one small company – envision the possibilities. To size up the situation, the United States Environmental Protection Agency estimates this country's daily potable water use in the landscape as greater than seven billion gallons, with over 50 percent of the water value unrealized; water lost in the landscapes due to inefficiencies, leaks and excess application beyond the plants water requirements. Even as water rates remain relatively low nationwide, the value of this lost water is approximately $10.2 billion dollars annually, more than enough to support this proposed new industry.

Managing landscape water is a daunting challenge requiring meticulous management of best management practices far beyond adjustment of irrigation control settings. To sustain the required reduction in water consumption in the landscape, water management professionals will need to provide comprehensive irrigation management, cultural practices in landscape maintenance will have to change, and dependency on potable water sources for purposes of irrigation will have to drastically reduce.

The *new* water manager will need to accept responsibility for overseeing all the necessary components required to maximize, measure and document sustainable water savings and success of the program. As a central "hub" for the landscape and irrigation service providers, the water manager will provide a central point of responsibility for maintaining water conservation practices that continues the mission, even as landscape service providers and property ownership change.

Water management professionals will have a strong education in agronomy with a thorough understanding of soil, oxygen and water relationships involved in active soil moisture management, allowing the opportunity to stretch the time between supplemental irrigation cycles to the next rain event. With a comprehensive understanding of the landscape's water requirements, the water manager will be equipped to direct landscape service providers with prescribed work scopes that complement water conservation. The water management professional will also be required to notify and escalate the need for irrigation repairs to property owners, providing them with the financial detail required by property managers.

While we have abundant SMART control products available to assist the professional water manager, in order to gain rapid adoption of the technology there will need to be a shift from product based sales strategy to performance based contracting. Federal and State water authorities are gearing conservation funding to support entities that produce and sustain measurable water savings over product rebate incentives of the past. The new water management industry is postured, at this very moment, to take advantage of this changed direction.

Acknowledging this would be a dramatic change in the actual control the landscape and irrigation professionals would gain with access to a new array of benefits provided from the water management professionals, allowing them the opportunity to focus their attention on providing services designed to enhance the overall water conservation program. In reality, this model would provide the ultimate control sought by these service providers, while limiting their perceived liability for failures of landscapes.

Irrigation professionals should realize a renewed role in water conservation through this model. Most people are keenly aware of the degradation of our country's water and wastewater infrastructure, but lack the understanding of the same degradation occurring in our abundant existing irrigation systems. Irrigation professionals are poised to provide massive renovation services of existing dilapidated irrigation systems, preparing these systems for new technology and best management irrigation practices. The irrigation industry will also be called upon to continue enhancing distribution and efficiency of irrigation systems.

Water authorities will look to the irrigation professional to provide routine water audits as necessitated by best management practices and to maintain the irrigation system integrity.
One of the key missions of the Irrigation Association should be to promote the use of their professionals by water utility providers performing landscape water audits. While many water utility providers offer water free audits to their customers, the program devalues the audit and water. Conservation incentives for water audits should be directed to the irrigation professionals as an incentive to align this important stakeholder group in the conservation program. Water utilities must be urged to mandate landscape water audits to instill value and respect our water resources deserve and enforce maintenance of the irrigation system infrastructure by property owners.

While irrigation system components are normally the focus of landscape irrigation water conservation, it is truly the landscape maintenance program that sets the basis for water conservation success or failure. Landscape service providers will be challenged with training their landscapes to be less dependent on potable water by implementing cultural changes to the way landscapes have been maintained in the past. In the short-term, a process to develop soil moisture holding capacity, aeration to enhance infiltration, designing nutrition programs that reduce growth but maintain plant color, promotion of root growth to expand the root zone water availability, and, increased mowing heights and reduced mowing frequency to reduce stress on plants during times of high temperatures. As a long term strategy, implementation of landscape replacement programs that begin to convert high water use plants with more resource efficient plants, including proper soil and irrigation modification to assure reduced water consumption, will enhance water conservation programs.

Conclusion

Water use in the landscape offers a tremendous opportunity for water savings due to the shear magnitude of water under utilized each day. Historically there has been an issue of responsibility and control of irrigation dividing the landscape and irrigation professionals, and driven by property owners. The creation of an industry of educated professionals managing water and orchestrating what has historically been a fragmented landscape and irirgation industry could provide the common ground for reducing the under utilized water in the landscape and gaining trust and respect from property owners and water authorities. In due course, this new water management industry will serve to reduce the pressure on our industry and landscapes by water utility providers, and ultimately save water while preserving our landscapes.

Landscape water management involves much more than controlling irrigation scheduling and will require dedicated commitment to best management practices by water managers, landscapers and irrigation professionals. Water utility providers will also play a significant role in the mass adoption of this industry through conservation incentives based on sustained performance satisfying their need for measurable success. Once this group of key stakeholders aligns, “hatchet” restrictions can be converted to incentives, as “Carrots taste better than sticks”.

It may be hard to imagine, but with projected rate increase for potable water the value of water lost in the landscape could surpass the total annual revenue generated by the landscape-green industry. Development of this new industry provides the landscape and irrigation professionals with a much greater assurance of protecting their respective livelihoods in the future, as well as maintaining our access to maintained green spaces for our enjoyment and well being.

Acknowledgements

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Return On Environment (ROE) – A New Evaluation Of Filtration Systems

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Abstract: As water supplies become increasingly scarce, alternative sources of water are becoming more common for irrigation use. Sources range from recycled wastewater to brackish groundwater – sources that until recently were not considered viable or economical. To make water from these sources suitable for irrigation, filtration is vital.

Filtration is also necessary for the successful long-term use of aquifer storage and recovery (ASR) systems, whose receiving formations must be protected from plugging with sediment. But filtration technologies themselves must be assessed for their environmental footprint – minimizing back flush water, reducing or eliminating chemical use, operating with a minimum of energy demand and requiring little infrastructure.

This paper will explore common filtration technologies in terms of their environmental footprint. Minimizing environmental footprint delivers a positive Return on Environment (ROE), which is an important companion to Return on Investment (ROI) in today's irrigation market.

Keywords: Filtration, suspended sediment, filters, environmental footprint, automatic self-cleaning, screen filters, microfiber filters, sand media filters, membranes, back-flush water, California Title 22.

The growing interest in alternative water resources – whether it's reclaimed irrigation or municipal wastewater, brackish groundwater, or the use of aquifer storage and recovery (ASR) systems – raises the bar for the performance of filtration systems. So does the growing use of more efficient irrigation systems, from high-efficiency sprinklers to microsprinklers and drip tape. We are drawing from increasingly challenging water sources and feeding ever more finely engineered systems – there is, literally and figuratively, no room for sediment or other contaminants.

Sediment, scale, algae and other contaminants in irrigation lines generate an array of costs for irrigators. Increased maintenance and costly clean-out of plugged heads, emitters or lines is easily identified as a direct cost. So is crop loss or turf damage from interruptions caused by plugged systems. But suspended solids in irrigation water can have other costs, too, such as tie-up of expensive fertilizers and other inputs, or higher-than-needed rates of acid or other cleaning solutions.

Adding to the challenge posed by lower-quality source water is the growing awareness of the ecological costs of supplying and treating water for irrigation. I refer to the Environmental Footprint of water treatment systems, which includes several key elements:

- Back flush water
- Chemical use
- Energy consumption
- Physical footprint.

Reducing the environmental footprint of a water treatment system means that irrigators need to consider not only their Return on Investment (ROI), but also their Return on Environment (ROE) – the balance between economy and ecology.

Time-Tested Options

The first step in evaluating filtration systems is reviewing the available options. For decades, agricultural and large-scale landscape irrigation systems have traditionally employed sand media filters. Simple and effective, this technology dates back to ancient times, and was modernized for use in municipal water systems in the early 1800s. Conventional screen filters are another choice for both small and large irrigation installations, though many require manual cleaning, which is labor intensive and may require a significant amount of water or chemicals.

The advent of automatic self-cleaning screen filters – which use the differential between pressure inside the filter and atmospheric pressure to push trapped particles out through suction nozzles – eliminated the labor requirement of conventional screen filters while operating much more efficiently than sand media systems.

The use of saline irrigation tailwater or brackish groundwater is also introducing membrane filtration to some irrigation operations. Membranes offer fine enough filtration to remove dissolved solids such as salt ions from water. They require high pressure and function best when they have a pre-filtration system – which could be any of the technologies mentioned above, or a microfiber or cartridge filter – to remove larger solids before the water enters the fine-, micro- or ultra-filtration stage.

Amiad is no stranger to protecting drip and other high-efficiency irrigation systems. The company was founded in the 1960s on an Israeli kibbutz, just as drip was being developed on nearby farms. As a desert nation with a highly intensive agricultural economy, Israel has long been at the forefront of water technology. Today, Israel leads the world in water recycling, re-using 75 percent of its water supply. (By comparison, the number-two water recycling nation, Spain, recycles 12 percent of its wastewater.)

Israel's leadership in water all aspects of water efficiency led Sandra Postel of the Global Water Policy Project to write, "Israel is the only nation that appears to have done what the world needs to do over the next 30 to 40 years – double water productivity in agriculture." The U.S. is at the cusp of that effort. Filtration will play a pivotal role in making it happen here, just as it has in Israel.

Environmental Footprint

We can gauge the Return on Environment by assessing the environmental footprint of a filtration system. Automatic self-cleaning screen filters use pressure to remove filter cake from their screens in a chemical-free process. Avoiding the need to store, handle and dispose of chemicals – whether they're cleaning agents or coagulants – is a significant environmental benefit. The ability of filters to optimize chemicals, as noted earlier, is also a factor of removing solids that can tie up chemicals in the system.

Energy use is minimal. Because there is little loss of head pressure, the irrigation system's pump or pressure is generally enough to operate the filter, and most of the systems have just a fractional-horsepower electrical motor to turn the suction nozzles in a spiral that cleans the entire screen. Some of the automatic self-cleaning filters are hydraulically operated, which means no electricity is necessary for their operation. That makes them extremely efficient, as well as well-suited for portability and isolated installations.

Physical footprint is another factor in environmental impact. Large installations – like those necessary for sand media filtration systems – take land out of production. They require concrete, rebar, pipe and other infrastructure, each element of which has its own environmental footprint. Utilizing a compact filtration system minimizes the need for infrastructure.

Certainly the most dramatic environmental footprint of a filter is the back flush water it produces to keep itself clean. Minimizing back flush water has always been important, and it is growing more critical today, especially in markets where water is scarce.

Many areas have enacted tight restrictions on what may be introduced – or returned – to surface water sources, whether reservoirs, ponds, creeks or canals. The result is that many irrigators find themselves required to build impoundments to capture their back flush water and let it infiltrate into the soil. Obviously, the greater the volume of back flush water, the larger the impoundments must be, and the more likely they will need more maintenance. There is also a significant public perception issue – neighbors and passers-by may be disturbed to see a large volume of water being disposed of, especially in areas or times of water use restrictions. That is no small matter in a world where water is a hot social, political and economic issue.

The benefit of automatic self-cleaning filters high efficiency – they produce just 25 percent of the back flush water that sand media systems do, or less than 1 percent of the flow – becomes extremely important in the context of back flush water's environmental footprint.

Managing Aquifers

Aquifer storage and recovery (ASR) systems offer a new option for managing water – "banking" supplies by injecting them into an underground reservoir for withdrawal when needed.

ASR systems have plenty of benefits. Banked water is protected from evaporation as well as contamination by animals or surface chemicals; its presence in the aquifer can also ward off intrusion by less desirable water, such as encroaching saltwater in many over-pumped coastal areas. And because all the public sees is a pump, the water is out of sight.

But pumping water into the ground cannot be "out of sight, out of mind," a lesson we have learned through our experience in the oil and gas industry. Produced water – wastewater – from oil and gas wells is typically disposed of underground in much the same way that ASR water is managed.

It is vitally important that solids are removed before the water is pumped into the aquifer, to avoid plugging the pores and cracks in the receiving formation that accepts water from the injection wells. Failing to adequately maintain the receiving formation can result in the need for costly cleanouts of the well or the need to drill new injection sites.

In many cases, water intended for ASRs also requires disinfection. As with multi-stage industrial water treatment processes, pre-filtration is an important step in maintaining the efficacy and efficiency of disinfection. UV systems are widely used to disinfect ASR water before injection. UV systems benefit tremendously from pre-filtration, as suspended solids can decrease transmittance of the UV rays, coat lenses, and even cast protective shadows over pathogens.

Injection systems have had excellent success with automatic self-cleaning filters, or – where the receiving formation is fine – with automatic microfiber (AMF) filtration systems. AMF technology allows filtration down to the two-micron level, using specially designed plastic cartridges wound tightly with microfiber. The fibers capture suspended sediments. When a pressure differential is reached between the inlet and outlet side of the filter, a high-pressure stream of water is directed at the plastic cartridge, which is grooved to deflect the stream through the fibers and carry away the particles. Like the automatic self-cleaning screen filters, the AMF produces relatively little back flush water, consumes, minimal energy and requires very little maintenance.

The 20-micron AMF system was recently approved by the State of California for achieving the turbidity level required under its Water Recycling Criteria, also known as Title 22. Coupled with an approved disinfection technology, the AMF can be used to treat wastewater for release into the environment in California.

Conclusion

The idea of treating wastewater – for release or for re-use – will become more commonplace in the years to come. The practice of achieving that treatment with the smallest possible environmental footprint will be a key factor in our success as we tap into alternative sources of irrigation water and use every possible drop well – and more than once. That will allow irrigation professionals to deliver a strong Return on Environment (ROE) as well as a healthy Return on Investment (ROI).

About the Author

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Directed Manipulation of Crop Water Status Through Canopy Temperature-based Irrigation Management

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Abstract. *While the relationship between canopy temperature and plant water status is well established, canopy temperature as a means of controlling crop irrigation has been limited in production applications due to the cost and complexity of temperature monitoring. A new low-cost infrared thermometry system, coupled with the BIOTIC irrigation protocol of the USDA/ARS allows for a biologically-based, simple, reliable and affordable approach to crop irrigation that is well suited to production agriculture. Beyond meeting the crop's water "needs", this system has shown promise for an ability to actively manipulate the water status of the crop to achieve desirable outcomes (e.g. product quality and water savings) that results in water-management derived improvements in the profitability of agricultural systems. Results from field level studies of full irrigation and managed deficits will be presented*.

Keywords. plant temperature, irrigation scheduling, BIOTIC, temperature signatures, water stress.

Introduction

Over the past decade there has been a growing awareness of the importance of water use by plants. This increased interest is, in part, a result of the realization that the world's water resources have been largely identified/exploited and that the prospect of additional freshwater becoming available is limited. While the idea of getting by with existing (and in some cases declining) water resources is indeed troubling, there is an element of hope in the fact that we have only begun to understand and research the responses of plants to limited water. Thus there is a great deal of opportunity to improve a number of aspects of plant water use. Since many of the wasteful uses of water that are common today are a result of a lack of alternative methods that are suitable for use in agricultural systems, the prospect of significant improvement is favorable.

Major opportunities for improving irrigation management include; residential uses (lawn and garden), large scale turf (landscaping and golf courses), plant production (nurseries and turf farms), horticultural and, perhaps most substantially, farming. While the volumes of water involved, the scales and means of production and the economic return on water vary significantly among these water uses, the plant is a common element. While in all instances, irrigation water is used by the plant, the plant itself has often been relegated to an ancillary position when it comes to irrigation decisions. Adoption of plant-centered irrigation management will hopefully improve the general reliability of irrigation management.

At this point it might be useful to make a distinction between methods used to measure/monitor water use in research settings versus those that are used by end-users to manage irrigation. Researchers can often employ methods without regard to economic and engineering considerations that would render the methods unsuitable for use in production settings. Production settings in this instance will be considered broadly as those end uses in which factors other than the scientific soundness of an approach might render it less than suitable for widespread practical use. In subsequent references "production settings" will be used to describe non-research applications of water management. Since our primary interest is in cropping systems on a production scale, the remainder of this paper will focus on research and production settings. The basic insights however should be directly applicable to a variety of other plant/irrigation systems.

Most methods for managing plant water use attempt to assess the water status of the plant by monitoring soil moisture or "environmental demand". The reliance on such approaches reflects the fact that it has generally proved to be rather difficult to directly monitor the water status of the plant in an efficient and cost-effective manner. The theory and engineering used for monitoring soil moisture and environmental demand (evapotranspiration) are quite advanced particularly with respect to automated use, and have proven to be adequate for a number of applications (Jones, 2007; Kirkham, 2004; Mullins, 2001). In spite of the advanced state of these methods, they have not been as widely adopted by end-users.

Irrigation management based on direct measurement of plant water status has been investigated (Jones 2004).There are theoretical advantages to the direct measurement of plant water status as a tool for the management of plant water use. In general, the more direct the link between the measured indicator and the object of manipulation, the more relevant and predictable the response will be. Plant transpiration can be measured by monitoring stem-flow or gas exchange (Lascano, et al., 1992; Trambouze and Voltz, 2001; Jones, 2004; Stockle and Dugas, 1992). These approaches can be automated and can provide continuous measurements over seasonal timescales however they are not always compatible with a wide range of plants and often are difficult to implement in production settings. Measurement of plant water content via relative water content or leaf water potential is relatively simple, though these methods have not proven to be amenable to automation or continuous measurement by end users.

The relationship between plant water use and the temperature of the transpiring leaves is, in many aspects, well characterized and plant canopy temperature has been used to monitor plant water status for many years. One of the primary obstacles to the wide use of plant temperature to characterize plant water status has been the relative difficulty in measuring plant temperature in the field. The utility of infrared thermometers (IRTs) for the measurement of canopy temperature was recognized in the 1970's and rapid advances in understanding the relationships between plant water status and canopy temperature resulted (Wanjura and Mahan, 1994; Pinter et al., 2003; Peters and Evett, 2004). While IRTs have been shown to be useful in field scale studies, the relatively high cost and complexity of the early devices often limited the number that could be used in studies.

In addition to the issues relating to the IRT hardware, the interpretation of the canopy temperature data is sometimes complex. Most efforts to utilize canopy temperature as an indicator of plant water status are based on assessing the plant temperature relative to a measured or modeled value of the temperature of a well-watered standard (Pinter et al., 2003). This approach results in estimates of water status based on comparison to a constantly variable temperature (air temperature or a calculated reference temperature). These temperature differences have been used to assess the water status of the crop. However, in spite of the proven utility of these approaches, they have not been widely adopted in production settings.

Over the past 20 years researchers with the USDA/ARS have developed BIOTIC, a method for assessing the water status of the plant by comparing canopy temperature to an estimate of the plant's optimal temperature that is based on the measured thermal dependence of metabolic functions. In the BIOTIC method, the optimal temperature value, which is a fixed characteristic of the plant species, is termed the "temperature threshold". The inclusion of an environmentally based time threshold accommodates irrigation intervals greater than one day. This method differs from previous approaches in that it uses optimal canopy temperature as an indicator of metabolic and water status optimality.

The BIOTIC protocol has proven to be successful in both high-frequency high-efficiency (e.g. drip) and lower-frequency lower-efficiency (e.g. sprinkler) irrigation systems. The BIOTIC protocol has been used to schedule irrigation with irrigation intervals ranging from 15 minutes to 7 days. While the level of control and optimality of the irrigation is reduced as the time between irrigations increases, the method does produce results that are comparable with soil moisture and evaporation/transpiration based methods on similar irrigation systems (Wanjura and Mahan, 1994; Wanjura et al., 1995; Mahan et al., 2005).

Though the theory of using canopy temperature as a tool for assessing plant water status is well developed, the measurement of canopy temperature under field conditions remained relatively expensive and time consuming. During the development of the BIOTIC protocol, the cost of IRT sensors declined significantly. In the initial phase, wired IRTs with a cost of ~$3,000/sensor were used. In the mid-1990's these sensors were replaced with thermocouple IRTs with a cost of ~$400/sensor. The need for wiring to connect IRTs to data loggers remained a significant impediment to the use of the IRTs in production settings. Wires and instruments placed in a field proved to be a constant source of aggravation for end users. Since many decisions in production settings will be viewed in terms of cost/benefit ratios, whenever unnecessary complexity can be eliminated adoption of the technology becomes more favorable. It thus became evident that even the best theoretical approach would be of limited value unless the theory was presented in a “package” of hardware and software that is compatible with the production setting in which it is to be implemented.

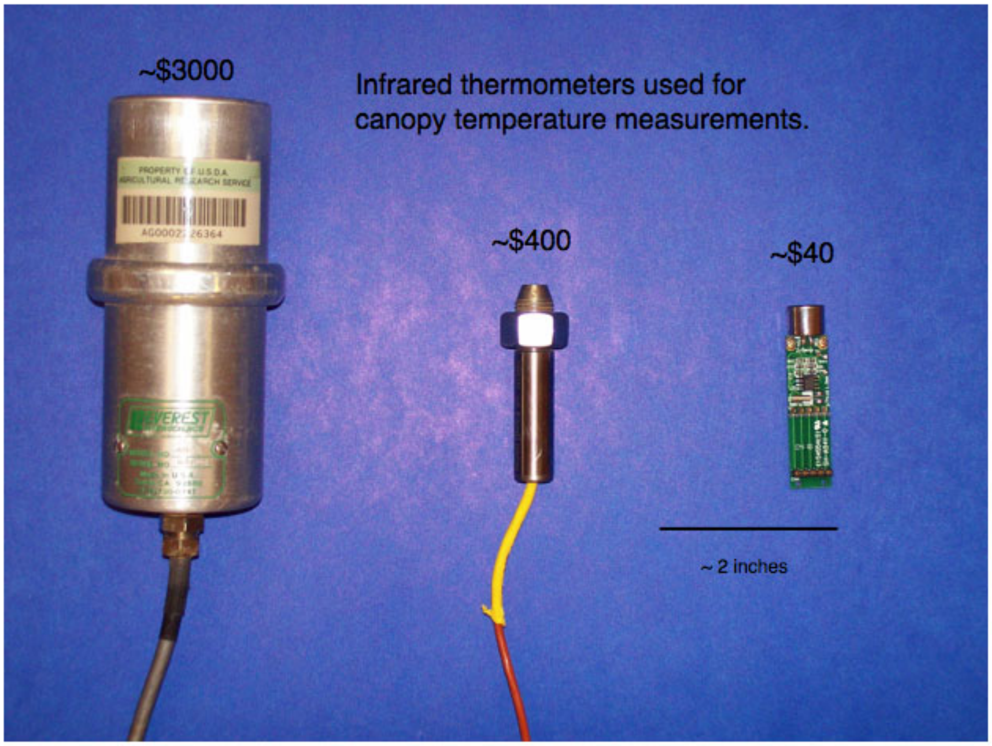

Figure 1. Infrared thermometers for canopy temperature measurement.

The challenges of continuous measurement of canopy temperature in research and production agriculture settings led us to develop a relatively low cost wireless infrared thermometry system. The system utilizes an infrared sensor that is approximately 1/10th the cost of infrared thermocouple sensors commonly used in agricultural settings (Figure 1). This low-cost sensor is capable of season-long measurements of canopy temperature that are comparable with those obtained with more expensive sensors (Mahan and Yeater, 2008). The low-cost IRT sensor has been incorporated into a “remote sensor” that monitors temperature on a short interval (60 seconds), collects the data for 15 minutes and then transmits the data (typically a 15 minute average) to a “base station”. The remote sensors are powered by a set of 4 “AAA” batteries that can power the units for approximately 90 days. The base stations used in this study are capable of monitoring up to 16 remote sensors. The remote sensor and the base station can effectively communicate at a range of 300m under most field conditions. Data collected by the base station can be manually downloaded to a computer or, more typically, a cell modem transfers the data at a set interval (typically 2 hours) to a website for archiving and graphical presentation.

Figure 2. Low-cost wireless infrared thermometry system for research/production use.

The performance of the system has been recently reported (Mahan et al., 2010). The wireless IRT system has now been used to monitor canopy temperatures at dozens of field sites over the past 2 years involving more than 100 remote sensors and 10 base units. The data collected by the remote sensors is generally high quality with no significant “drift” over time. The IR sensors have been demonstrated to produce data of equal quality to more commonly used infrared thermometers that can be significantly more expensive (5X to 10X). This wireless IRT system (figure 2) is currently available commercially from Smartfield (Smartfield.com). The combination of the wireless data transmission and the reduced cost temperature sensor should allow researchers and producers to deploy a larger number of temperature measuring devices in a simpler installation and at a lower cost than has been previously possible. It is hoped that this technology will help to make seasonal measurement of canopy temperatures a more routine part of plant stress studies.

At present, utility of the BIOTIC approach for full irrigation is well-documented (Wanjura and Mahan, 1994; Wanjura et al., 1995; Mahan et al., 2005) and the protocol has been commercialized. While BIOTIC (and other irrigation approaches) are often capable of providing irrigation management particularly under conditions that require full irrigation, there is a growing need for irrigation management tools that are designed to provide for the imposition of controlled water deficits. The need to reduce water application can have many sources including; declining water resources, increasing water costs, governmental regulation and drought resistant germplasm. Regardless of the circumstance necessitating the reduction in irrigation, an ability to establish and maintain plant water status at desired levels offers the promise of a new approach to water management and plant production.

Deficit irrigation has been a common practice in crop production for many years in many regions. Most often deficit irrigation is a strategy that is thrust upon producers as opposed to an approach that is voluntarily adopted for a specific purpose. Given that most irrigators are happy to accept additional water (as rain or irrigation) whenever it is available the idea of deliberate, managed deficit irrigation will be a “hard sell”.

The largest advantage to full irrigation is that at the upper end of the irrigation regime (in terms of yield and applied water), yield becomes relatively less sensitive to variation in water application than it is on the lower end of the curve where yield and water application are almost linearly related. When a producer makes the decision (voluntarily or under duress) to move away from full irrigation to a managed deficit, the ability to control that deficit becomes critical. To move too far in the direction of deficits raises the risk of incurring a larger than anticipated yield reduction while the application of irrigation above that intended will result in no reduction in water use. While it is clearly possible, and in some cases no doubt advantageous, to reduce irrigation amounts in a controlled manner, many of the approaches that could be used to accomplish this are perhaps not fully compatible with crop production settings.

We propose that canopy temperature will provide a useful and practical approach for establishing and controlling desired water deficits in production settings. The ability to modify the BIOTIC approach to deficit irrigation management is attractive from the point of view that the theory and instrumentation that has been previously developed should be adaptable to deficit irrigation. During the development of the BIOTIC concept, the sensitivity of the irrigation scheduling with respect to temperature and time thresholds was investigated over several years. These studies demonstrated that optimal water application and plant performance were associated with specific combinations of temperature and time thresholds. It was demonstrated that as the temperature threshold was altered to include values below and above the biologically-identified optimal value the amount of irrigation water applied declined with increasing temperature thresholds. The canopy temperature of the crop increased generally with declining water application and the period of time that canopy temperature was optimal. Similarly, increasing the time threshold for irrigation events resulted in increases in stressful canopy temperatures as well as declines in the amount of water applied. Thus it was established that certain combinations of temperature and time thresholds resulted in what was considered to be optimal water management and others resulted in less than optimal water with respect to yield. While the previous studies used non-optimal threshold combinations to demonstrate the optimality of the correct settings, they also demonstrated the potential for the use of non-optimal threshold pairings to manipulate the water status of the crop outside the range of optimality.

The goal of this study was to investigate the utility of a modified BIOTIC approach for the detection of differences in canopy temperature resulting from various deficit irrigation regimes in cotton and sorghum. Three questions were posed in this study.

1) Is the low cost wireless IRT system reliable and accurate enough to detect seasonal patterns of water deficit in terms of canopy temperature?

2) Can irrigation regimes be identified from seasonal canopy temperature patterns?

3) Do canopy temperature patterns differ between short interval drip and long interval pivot irrigation systems?

Materials and Methods

It should be noted that the objective of this study was to assess the use of the wireless IRT system to detect and assess canopy temperature differences. It was not a physiological study of plant water stress but rather an effort to identify and analyze the changes in seasonal canopy temperature that were associated with different irrigation approaches.

Cotton and sorghum, two crops commonly grown in the southern high plains region of Texas, were chosen for this study. Both crops are responsive to irrigation over a relatively wide range and are particularly amenable to deficit irrigation approaches.

Crops were grown on a production farm near Plainview, TX (2008 and 2009) and on a USDA/ARS research facility in Lubbock, TX. (2008). Cotton was grown at both the Lubbock and Plainview sites and sorghum was grown only at the Plainview site. At the Lubbock site, cotton was irrigated with a subsurface drip irrigation system. Irrigation was scheduled with a BIOTIC irrigation approach designed to apply a full irrigation regime. Under the full irrigation regime, 6mm of water was applied in response to each irrigation signal. Reduced irrigation treatments consisted of applications of 4mm and 2mm in response to each irrigation signal in the full irrigation treatment. A rainfed treatment that received only rainfall was included.

Irrigation at the Plainview site was designed to provide irrigation amounts of 85%, 65%, and 50% of ET as estimated by the producer. The irrigation amounts were established by the producer in a production field to gauge the potential for water savings in the crops. It is important to note that these are the “target” amounts set by the producer based on his knowledge of the irrigation and cropping system and do not represent research-based values. The irrigation amounts were produced by installing specific sprinkler nozzles at various points along the pivot. The pivot was operated in a 5-day cycle.

Canopy temperature was monitored in Lubbock cotton over a 34-day period from July 14 to August 17 (DOY 196 to DOY 230). During this interval the cotton canopy was uniform and background soil was not routinely observed.

Canopy temperature of cotton in Plainview was monitored over a 93-day period from July 7 to October 18 (DOY 188 to DOY 281) in 2008. Canopy temperature of cotton and sorghum was monitored over a 78-day period from June 25 to September 11 (DOY 176 to DOY 254) in 2009. Some bare soil background was observed in the first 2 weeks of the monitoring interval in 2009.

Temperature measurements were initiated when the seedlings had emerged and sufficient leaf area was present to fill the field of view with the remote sensors placed ~10 cm from the canopy. The height of the sensors was adjusted weekly to maintain a distance of 10 cm to 20 cm from the canopy. The field of view of the remote sensors is specified as 1:1 by the manufacturer and the diameter of the “spot size” of the measurement varied from 10 cm to 20 cm. Canopy temperature was monitored once per minute and 15 minute averages were collected. This provided 96 measurements per day for the duration of the study.

Results and Discussion

Low cost wireless infrared thermometry systems, such as the one previously described, have the potential to make it easier and cheaper to monitor canopy temperatures on seasonal scales in research and production settings. Season-long monitoring of canopy temperatures at 15-minute time intervals can provide relatively detailed information about the magnitude of thermal variation, the temporal pattern of variation and the spatial variation in temperature.

The deployment of multiple sensors with fully automated data management allows for the collection of datasets with thousands of observations. Given the magnitude of the data that can be collected, a graphic visualization approach is perhaps the most useful means to initially explore the relationships between canopy temperature and the water and metabolic status of the crop.

Perhaps the most common approach to visualization of canopy temperature involves graphical presentation of the canopy and air temperature as a function of time (figure 3). While such a graphic is easy to produce, its most dominant visual feature is the diurnal trend of temperature (reminiscent of a sine wave) that serves to mask water-related temperature variation. Thus the utility of such a presentation of the data for assessing crop water status is limited in two respects; 1) the diurnal variation becomes the dominant pattern even though, at least 50% of the data presented (night data) is not directly indicative of the water status of the crop and 2) there is no indication of the metabolic ramifications of specific temperatures.

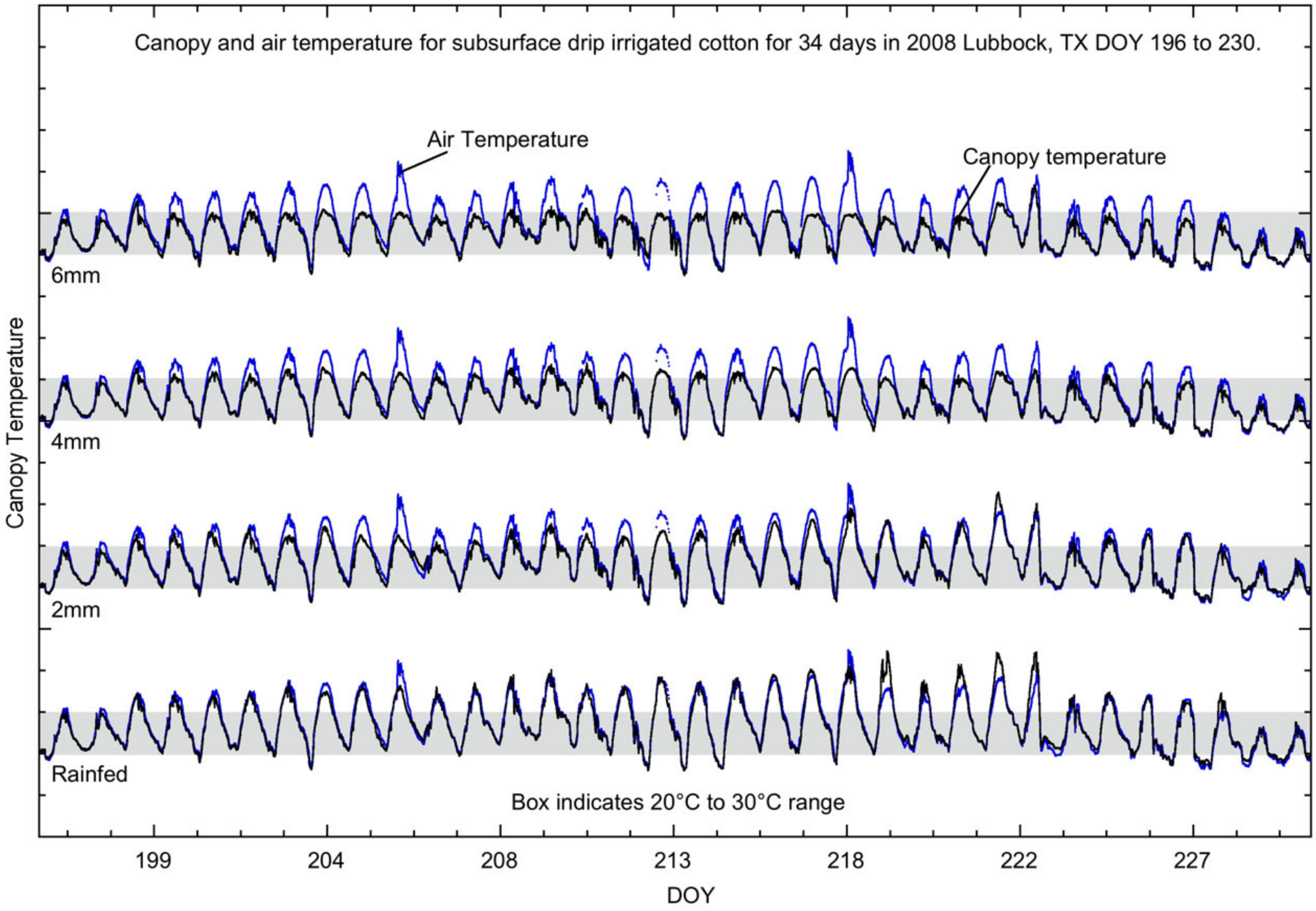

Figure 3. Canopy and air temperatures for cotton grown under 4 levels of irrigation with subsurface drip. Irrigation amounts were 6mm, 4mm, 2mm and rainfed provided on daily irrigation interval in Lubbock, TX in 2008.

With respect to the diurnal temperature pattern that includes a large amount of data that is not directly indicative of water status, it is a simple matter to reduce the dataset by excluding night temperatures. The removal of night data serves to “break” the diurnal pattern making it easier to focus on the water-related temperature variation.

While eliminating temperatures that do not relate to water status reduces the visual clutter on the graph, it does not convey information on the potential effect of specific temperatures on the metabolism of the plant. The metabolic ramifications of the thermal variation can be incorporated into the analysis by comparing the canopy temperatures to a base temperature that is based on a metabolic indicator. According to the BIOTIC protocol, canopy temperatures in excess of the biological optimum are a useful indicator of water deficits in crop plants. In figure 4, canopy temperatures have been filtered to remove values that are below 27°C which is 1°C less than the 28°C BIOTIC temperature optimal for cotton. Temperature scale is indicated by a shaded “bar” with a range from 28°C to 30°C and temperatures above the optimal temperature “bar” indicate potential metabolic stress.

Applying these modifications to a graphic presentation of canopy temperatures reduces the amount of data that is displayed by ~50% which enhances the viewers ability to see the relationships between canopy temperatures and water deficits and metabolic stress. The numerical axes have been removed and replaced with a shaded “bar” that indicates both the temperature scale and optimal thermal range and the figure has been annotated to provide information that is needed for comparisons. When “filtered” with regard to optimal temperatures and those that could be associated with water deficits, the pattern of canopy temperature provides a view of the magnitude of stresses and the temporal pattern of the stresses. We refer to these filtered multi-day temperature patterns as “temperature signatures” for the periods of interest. Since a large number of temperature signatures can be arranged on a single page, the arrangement of small multiples allows rapid visual comparisons of relationships among crops, water treatments, irrigation systems and years.

It is proposed that canopy temperature signatures provide a useful method for analyzing seasonal thermal patterns in terms of differences and similarities among environments and irrigation treatments. Figure 5 shows the canopy temperature signatures of this irrigation management study involving multiple irrigation treatments in drip and pivot irrigation systems on cotton and sorghum over 2 years at 2 locations. In addition to the canopy temperatures, the air temperature over the measurement period at each site is indicated. Each of the treatments in the study is discussed below using the canopy temperature signatures as a guide for inspection.

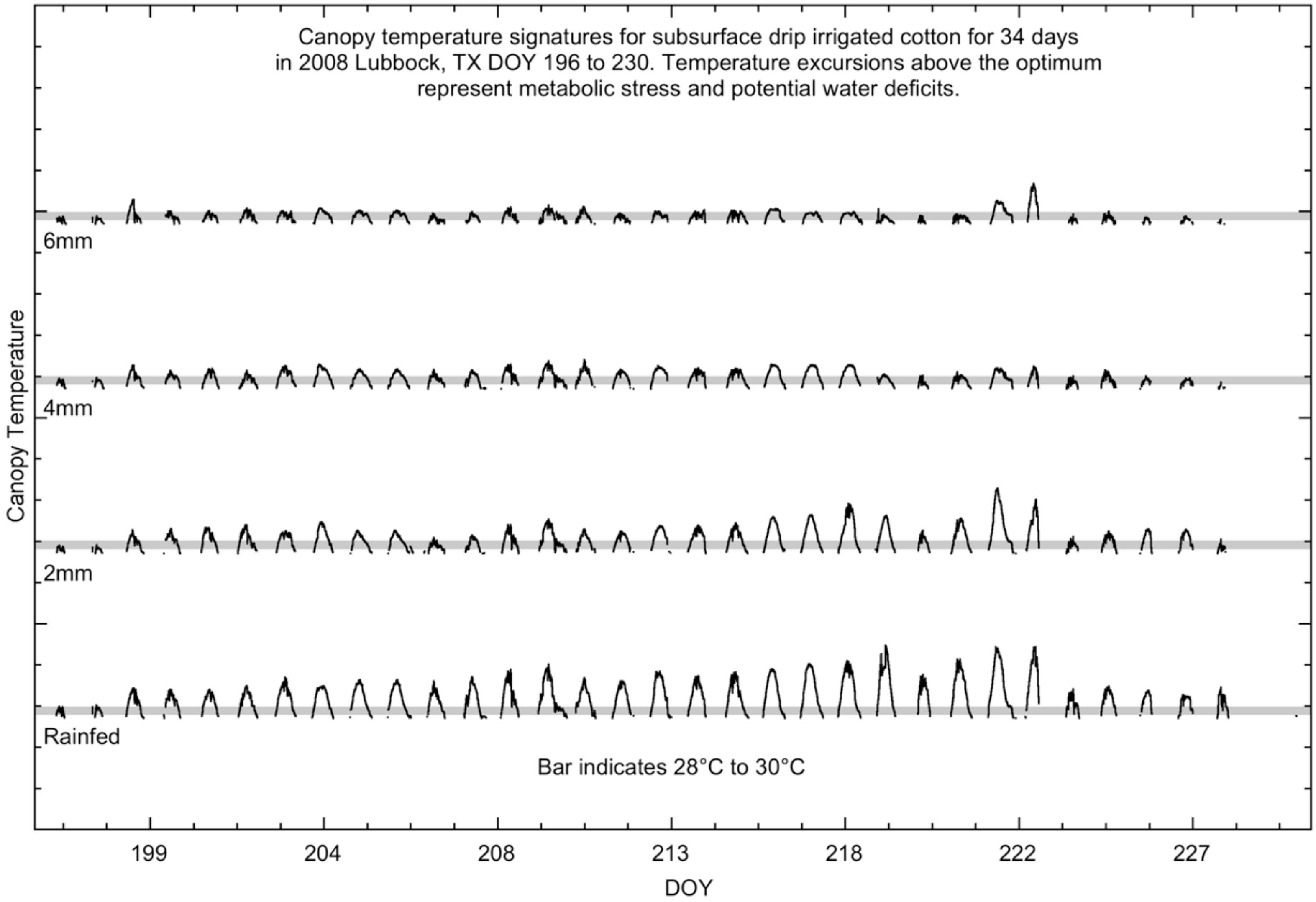

Figure 4. Canopy temperature signatures for cotton grown under 4 levels of irrigation with subsurface drip. Irrigation amounts were 6mm, 4mm, 2mm and rainfed provided on daily irrigation interval in Lubbock, TX in 2008. Canopy temperatures were "filtered" to show temperatures above 27°C. Shaded bar indicates optimum temperature range based on metabolic indicators.

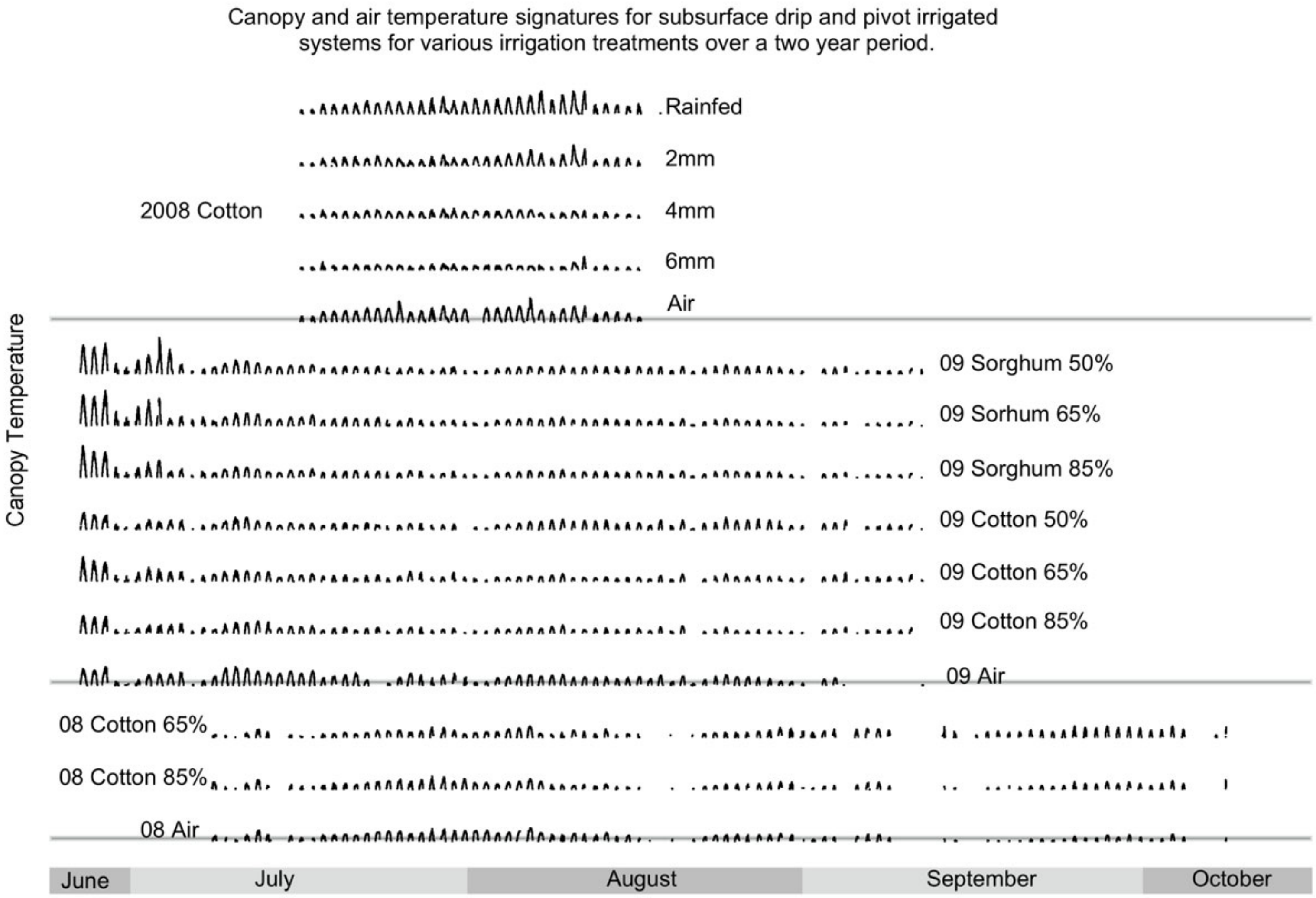

Figure 5. Canopy temperature signatures with air temperatures for cotton and sorghum grown under various levels of subsurface drip and pivot irrigation in 2008 and 2009. Canopy temperatures were "filtered" to show temperatures above 27°C. Shaded bar indicates optimum temperature range based on metabolic indicators.

2008 Cotton (research drip)

During the 34-day measurement interval the temperature signatures differed across all 4 irrigation treatments. There is an evident trend of increasing canopy temperature as irrigation amount declined from 6mm/day to rainfed.

2008 Cotton (production pivot)

During the 93-day measurement interval in 2008 the 85% and 65% canopy temperature signatures were generally similar with treatment differences apparent during only 3 periods. The first period occurred in late July canopy temperatures in the 85% treatment were elevated slightly compared to the 65% treatment. The second period included four days in the beginning of September and the third period was 23 days in late September and early October when the canopy temperatures in the 65% treatment were warmer than in the 85%. Yield differences between the treatments were negligible indicating that significant water deficits did not develop as evidenced by the canopy temperature signatures for the treatments.

2009 Cotton (production pivot)

During the 78-day measurement interval in 2009 the 85% and 65% canopy temperature signatures are generally similar. A pattern that is similar to that seen in a similar irrigation treatment in the 2008 season. The canopy temperature signature of the 50% treatment was similar to that of the 85% and 65% treatments with the exception of the elevated temperatures during the end of June and early July (possibly a soil background anomaly). While final yields are not yet available for the treatments, indications are that the 85% and 65% will be very similar with a slight reduction in the 50%.

2009 Sorghum (production pivot)

During the 78-day measurement interval in 2009 the 85% and 65% canopy temperature signatures are generally similar. (essentially the same result as seen in the 2009 Cotton treatments). The canopy temperature signature of the 50% treatment was warmer than the 85% and 65% treatments during a 12-day period in late August. Once again while final yield data is not yet available, the perception of the farmer is that the yield differences are minimal

Subsurface drip and pivot irrigation systems were used in this study. The subsurface drip system applied 6mm or less of water on a daily interval while the pivot system applied approximately 25 mm of water on a 5-day interval. The subsurface drip treatments were applied in a research setting and were precisely measured. The pivot system was in a production field and the irrigation regime, while not quantitatively rigorous, represents the upper echelon of production pivot irrigation management in the southern high plains of Texas.

In the subsurface drip treatments, the different irrigation regimes were readily apparent in the canopy temperature signatures with all 4 irrigation treatments evident in the canopy temperatures over the entire measurement period. Since daily irrigation amounts were similar to daily potential ET for the crop, the amount of water applied was sufficient only to meet the needs of the crop on a daily time scale. Thus canopy temperature signatures would be expected to be sensitive to plant water status on the daily time scale.

In the pivot irrigation system, the canopy temperature signatures were surprisingly similar across the irrigation treatments in the various years and crops. The lack of clear and systemic differences in canopy temperature signatures could be interpreted in two ways. Interpretation #1 is that the irrigation treatments imposed levels of water stress over the season that were in line with the intended water applications and that the canopy temperature measurements did not reflect the varying water status of the crop. Interpretation #2 is that, while the water applications did vary relative to one another, the PET estimates that were used to establish the treatment were incorrect and resulted in a range of irrigation amounts that did not represent significant deficits. For instance, if the 85% treatment was really closer to 100% then the 65% and 50% treatments may have actually applied 76% and 60% respectively.

While interpretation #1 cannot be eliminated at this point in time, the pattern of canopy temperature signatures in the subsurface drip system suggests that water differences of the magnitude intended in the pivot studies could be detected with the IRT system used in the studies. Additionally, the absence of significant differences in yield and plant performance among pivot irrigation treatments suggests that water deficits under the pivot were not of the expected magnitude.

If indeed interpretation #2 is correct, this would serve to underscore the difficulties inherent in deficit irrigation management in production systems and perhaps indicate the utility of canopy temperature signatures in the post-hoc interpretation of deficit irrigation results.

Conclusions

It is well established that measurement of canopy temperature is a potentially useful tool for the detection of water deficits in a wide variety of plants for a variety of end uses. Biologically-based estimates of optimal plant temperature may provide a useful approach to assessing the impact of temperature variation on a mechanistic level. Biologically-based temperature optima coupled with continuous measurements of canopy temperature provide a means of identifying and quantifying water-related elevations in canopy temperature.

The recent development of a relatively low-cost wireless infrared thermometry system has greatly simplified the process of continuously monitoring plant canopy temperature on seasonal time scales in both research and production environments. It is hoped that such devices will serve to make canopy temperature measurement a routine undertaking in research and production settings.

Canopy temperature signatures based on optimal temperature estimates provide a method for visualizing and inspecting seasonal patterns of canopy temperature. Initial efforts indicate that canopy temperature signatures can be used to identify and quantify water deficits in subsurface drip and pivot irrigation systems.

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Irrigation scheduling by soil water potential

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Abstract. One of the fundamental ways to schedule irrigation is through the monitoring and management of soil water potential (SWP). Soil water tension (SWT) is the force necessary for roots to extract water from the soil and growers find it easier to deal with the positive units of SWT rather than the negative units of SWP. With the invention of tensiometers, SWT measurements have been used to schedule irrigation. There are seven different types of field instruments used to measure SWT, either directly or indirectly. Specific SWT criteria for irrigation scheduling have been developed for the production of individual vegetable crops, field crops, trees, shrubs, and nursery crops and for the management of landscape plants. A review of the known SWT criteria for irrigation scheduling will be presented.

Keywords. Soil water tension, Tensiometer, Granular matrix sensor

Why Measure Soil Water Tension

The lack of water in plant-top tissues is transmitted through the plant, down into the roots, and into the soil. The measurement of soil water tension can be closely related to the stress experienced by the plant tissues, and in these conditions irrigation scheduling based on soil water tension can be directly related to plant performance. The use of a soil water tension measuring device provides a continuous measurement analogous to the force (suction) necessary to extract water from the soil.

When growers irrigate too infrequently and with too much water, product yield and quality is lost (Tjosvold and Schulbach 1991) and water and nutrients are lost, with the potential of environmental harm. Since SWT is closely related to plant stress, crop yield and quality is closely related to SWT irrigation criteria (Shock et al. 2007b). Careful irrigation scheduling by SWT simultaneously provides the grower with a tool to optimize income and minimize negative off site effects of irrigation.

Instruments to Measure Soil Water Tension

Soil water tension has been measured directly with tensiometers and through indirect methods such as with gypsum blocks, granular matrix sensors (GMS, Watermarks), porcelain resistance to air movement (Irrigas), psychrometers, pressure plates, and dielectric sensors coupled with porous media (MPS-1).

The Response of Specific Crops to SWT Irrigation Scheduling

The specific SWT irrigation criteria chosen for each crop should be based on experience with the crop in a given region. The climate, soil type, irrigation system, and sensor placement can affect the optimal irrigation criteria.

Response of Onion

Onion is a shallow rooted crop requiring relatively wet soil (Table 1). The response of vegetable crops to SWT has been reviewed (Shock et al. 2007b). For short-day onion, the irrigation criterion has varied from 8.5 to 45 cbar depending on the climate, soil, and irrigation system. Sandy soil and drip irrigation systems necessitate wetter irrigation criteria. When and where rainfall is significant, onion production is favored by slightly drier irrigation criteria. The irrigation criterion for long-day onions on silt loam has varied from 10 to 27 cbar. When rainfall is absent, wetter criteria are favored. Furrow irrigation requires drier criteria due to the risk of bulb decomposition in excessively wet parts of fields. Increasing water stress (increased SWT) in the later part season in an attempt to reduce onion bulb decomposition reduced bulb yield and grade (Shock et al. 2000b). Onions are particularly sensitive to losses in yield and grade from small amounts of water stress when infected by iris yellow spot virus (Shock et al. 2009).

Table 1. Soil water tension (SWT) as irrigation criteria for onion bulbs.

SWT, cbar	Location	Soil type	Irrigation system	Soil moisture sensors, depth	Citation
8.5	Piaui, Brazil	sandy	micro sprinkler	tensiometer	Coelho et al., 1996
10	Pernambuco, Brazil		flood	tensiometer, gravimetric	Abreu et al., 1980
15	Sao Paulo, Brazil	sandy and clay	furrow	gravimetric	Klar et al., 1976
10 to 15	Oregon	silt loam	drip	GMS	Shock et al., 2009
17 to 21	Oregon	silt loam	drip	GMS	Shock et al., 2000a
27	Oregon	silt loam	furrow	GMS	Shock et al., 1998a
45	Karnataka, India	sandy clay loam		tensiometer, gravimetric	Hegde, 1986

Response of Potato

Potato is also shallow rooted requiring relatively wet soil (Table 2). Precise irrigation of potato has been closely related to many tuber quality attributes (Shock et al, 2007a). Wetter irrigation criteria are needed on sandy soils. Silt loam soils should be maintained slightly drier. Where drip irrigation is applied frequently, the irrigation criteria for silt loam is wetter (25-30 cbar) than where sprinkler or furrow irrigations systems are used (50-60 cbar).

Table 2. Soil water tension (SWT) as irrigation criteria for potato.

SWT, cbar	Location	Soil type	Irrigation system	Soil moisture sensors, depth	Citation
20	Western Australia	sandy loam	sprinkler	tensiometer	Hegney and Hoffman, 1997
25	Maine	silt loam	sprinkler	tensiometer, gravimetric	Epstein and Grant, 1973
25	Northern China		drip	Tensiometer	Wang et al. 2007
30	Oregon	silt loam	drip	GMS	Shock et al., 2002b
50	California	loam	furrow	tensiometer	Timm and Flockner, 1966
50 to 60	Oregon	silt loam	sprinkler	GMS	Eldredge et al., 1992, 1996; Shock et al. 1998b, 2003
60	Oregon	silt loam	furrow	GMS	Shock et al., 1993

Response of Cole Crops

Cole crops are among the species most sensitive to soil water tension (Table 3). Irrigation criteria as wet as 6 to 10 cbar are recommended in Arizona.

Table 3. Soil water tension (SWT) as irrigation criteria for cole crops.

Common name	SWT, cbar	Soil type	Irrigation system	Soil moisture sensors, depth	Citation
Broccoli	10 to 12	sandy loam	drip	tensiometer	Thompson et al., 2002a, b
Broccoli	50, 20[b]	silt loam	lysimeters	gypsum blocks	Maurer, 1976.
Cabbage	25	loamy sand and sand	lysimeter	gypsum blocks	Smittle et al., 1994
Cauliflower	10 to 12	sandy loam	drip	tensiometer	Thompson et al., 2000 a, b
Cauliflower	25[a]		furrow and flood		Prabhakar and Srinivas, 1995.
Cauliflower	20 to 40	various			Kaniszewski and Rumpel, 1998
Collard	9	sandy loam	drip	tensiometer	Thompson and Doerge, 1995
Mustard, greens	6 to 10	sandy loam	drip	tensiometer	Thompson and Doerge, 1995
Mustard, greens	25[a]	loam sand and sand	lysimeter	gypsum blocks	Smittle et al., 1992

[a] 25 kPa was the wettest irrigation criterion tested.
[b] SWT of 50 during plant development, then 20 during head development.

Response of Other Field and Vegetable Crops

The published SWT irrigation criterion for other crops is listed in table 4. In the case of sweet potatoes, the recommendation is to irrigate at 25 cbar during early plant development, then switch to a much drier criteria for potato development. These recommendations contrast with potato, where the soil is maintained a more constant SWT throughout development, and where some limited stress on early vegetative plant growth favors potato vine health and tuber quality (Cappaert et al. 1994; Shock et al. 1992).

Thomson and Fisher (2006) used SWT irrigation criteria of 60 cbar for developing ET irrigation scheduling for cotton in Mississippi.

Table 4. Soil water tension (SWT) as irrigation criteria for Other Field and Vegetable Crops

Common name	SWT, cbar	Soil type	Irrigation system	Soil moisture sensors, depth	Citation
Beans, snap	25[a]	loamy sand	lysimeter	gypsum blocks	Stansell and Smittle, 1980
Carrot	30 to 50		sprinkler	TDR[b]	Lada, 2002
Carrot	40 to 50		micro sprinkler	GMS	Lada and Stiles, 2004
Lettuce, romaine	<6.5	sandy loam	drip	tensiometer, 30, cm	Thompson and Doerge, 1995
Lettuce, leaf	6-7	sandy loam	drip	tensiometer, 30 cm	Thompson and Doerge, 1996a, b
Lettuce	<10	red earth	drip	tensiometer, 30 cm	Sutton and Merit, 1993
Lettuce	20	clay loam	sprinkler, drip	tensiometer, 15 cm	Sammis, 1980

Lettuce, romaine	30	clay loam	n.a.	tensiometer and gypsum blocks, 30 cm	Aggelides et al., 1999
Lettuce, crisphead and romaine	50	sandy loam	sprinkler	tensiometer, 15 cm	Gallardo et al., 1996
Spinach	9	sandy loam	drip	tensiometer	Thompson and Doerge, 1995
Squash, summer	25[a]	loamy sand and sand	lysimeter	gypsum blocks	Stansell and Smittle, 1989
Sweet corn	20		drip		Phene and Beale, 1976
Sweet potato	25, then 100[c]	loamy sand and sand	lysimeter	gypsum blocks	Smittle et al., 1990
Tomato	10	fine sand	drip	tensiometer	Smajstrla and Locasio, 1996
Tomato	20	sand	drip	tensiometer	Oliveira and Calado, 1992
Watermelon	7 to 12.6	sandy loam	drip	tensiometer	Pier and Doerge, 1995a, b

[a] 25 kPa was the wettest irrigation criterion tested.
[b] TDR, time domain reflectrometry.
[c] SWT of 25 during plant development, then 100 during root enlargement.

Response of Poplar Trees

Poplar tree growth is favored by an irrigation criterion of 25 cbar and drier criteria lead to reduced tree and biomass production (Shock et.al. 2002).

Response of Wine Grapes

Recently the viticulturist of Camalie Vineyards, Napa, California, has demonstrated potential usefulness of SWT data for the production of quality grapes (Holler 2008). Wine grapes are a case where controlled and managed water stress is related to crop quality.

Response of Cranberries

Jeranyama (2009) reports that cranberries require SWT in the range of 2 to 6 cbar in the morning and 2 to 10 cbar in the afternoon. Surprisingly soil consistently wetter than 2 cbar is too wet.

Response of Strawberries

Strawberries are extremely sensitive to water stress. A SWT irrigation criterion of 10 cbar has been recommended (Serrano et al. 1992).

Response of Flower Production and Ornamental Plants

The production of nursery plants and flowers grown in artificial medium is particularly vulnerable to loss of water and nutrients from excessive amounts of irrigation (Tjosvold and Schulbach 1991; Oki et al. 1995). Soil often needs to be maintained in the range of 1 to 6 cbar (Kiehl et al. 1992; Plaut et al. 1976). Plaut et al. showed that the medium needs to be maintained wetter than 6 cbar for cut roses. Oki et al. demonstrated that smaller irrigations at wetter SWT using tensiometers resulted in much more productive rose productivity.

Carnations grown in raised beds responded well with growth medium maintained in the 0 to 10 cbar range (Marsh et al. 1962). Tensiometers needed to be designed to be accurate and responsive in the 0 to 10 cbar range.

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Rainwater Harvesting – American Rainwater Catchment Systems Association

The American Rainwater Catchment Systems Association is a national organization dedicated to promoting the use and benefits of rainwater catchment through education and outreach programs. Rainwater catchment primarily involves catching rain from an impervious surface and transferring it to a storage unit to hold the water for use at a later date. Collecting rainwater not only provides a decentralized system that gives independence to the user, but also helps the community by decreasing the demand from centralized water supply systems, which aids in recharging aquifers. As an easily maintainable way to retain and detain water at a low cost, rainwater catchment can be a valuable tool to supplement landscape irrigation during seasonal and drought-related water restrictions. It can also be utilized for storm water management when creating a Low Impact Design (LID). Today, many irrigation professionals are incorporating rainwater system installations into their range of services.

Rainwater harvesting has a long history and collecting rainwater in cisterns was a common method of providing water for many of the first settlers in Texas. Much has changed in the last century since cities sprang up, wells dug, lakes built and municipal water supplies were established. Springs have reduced their flow or dried up, rivers are more polluted and base flow has decreased in Texas rivers due to population growth, water and food demands. Texas lands are now more dominated by houses, streets and impervious cover due to population growth and urban sprawl. Rangeland too is more dominated by woody plants and shorter grasses due to the absence of fire and heavy grazing pressure by livestock for the last 125 years. This increases water runoff and decreases water infiltration. All of this impacts the issue of water quantity and quality facing our state today. Today, there is new interest in rainwater harvesting.

The Renewed Interest in This Time-Honored Water Resource Is Due To:

- concern of having enough high quality water available now and the future,
- rising environmental and economic costs of providing water by centralized water systems or by well drilling;
- health concerns linked to the source and treatment of water;
- cost efficiencies associated with rainwater harvesting; and,
- rainwater's purity;

COLLECTING WATER FOR LANDSCAPE PETS, LIVESTOCK, WILDLIFE AND IN-HOME POTABLE AND NON-POTABLE USES

Captured rainwater can be used for watering landscape, gardens and to provide water for pets, wildlife and livestock. Additionally, rainwater can be filtered, sanitized and used for non-potable and potable water uses in homes, and businesses instead of other sources of water. The process is simple and often less expensive than drilling a well.

HOW MUCH RAINWATER CAN YOU COLLECT?

You can estimate the amount of rainwater that can be harvested from a catchment surface (defined as any surface used to collect rainwater such as a roof) with the following calculation:

There is approximately 0.6 gallons of water that falls on each 1 square foot of roof area in a 1 inch rain. A 1000 square foot roof could yield (1000 x .6 =) 600 gallons of water for each inch of rainfall.

WATER USES

Landscape Usage: Drip irrigation is most practical when using rainwater for landscape irrigation. It can often be applied by gravity pressure alone or used in combination with mechanical equipment.

Wildlife Watering*:* Water guzzlers are rainwater collection systems built in remote areas to water wildlife. A roof, storage tank and watering device are all that are needed. Rainfall could also be collected off existing barns, deer blinds or other structures and used to water wildlife.

Water for Livestock and Pets*:* Livestock require great quantities of water on a daily basis. A horse or cow can consume 7 to 18 gallons of water a day and a large herd would demand hundreds or more daily. Smaller herds or individual animals or pet water demands can be met with collected rainwater.

Water for the Home*:* Rainwater currently supplies many homes worldwide with an abundant supply of good, soft, safe water to drink and use. Storage capacity needs to be sufficient to provide several months supply of water. A good filtering and sanitizing system needs to be installed and maintained to provide high quality potable water for the home. Non-potable uses inside the home include commodes, and clothes washers. Rainwater can meet this demand and reduce your municipal water requirements.

ARCSA “Accredited Professional”

ARCSA began an “Accredited professional” (AP) program in the summer of 2007. The program consists of an approved application, passing a 100 question test, ARCSA membership and attending a 2 day workshop. Once approved, APs are listed on the ARCSA website and are allowed to promote themselves as APs. The workshop has been approved by a number of organizations for Continuing Education Units (CEUs) as well. Plans are to add a more advanced level in 2010 with additional, training, more difficult test and proof of installing a certain number of acceptable installations. There have been over 900 individuals trained since the program began and there have been 10 workshops held in 2009 from the Florida Keys to Bellingham Washington and places in between. ARCSA is also working with various state and national agencies in developing acceptable wording in the inclusion of rainwater harvesting in codes, regulations and guidelines.

CONCLUSION

Captured rainwater has a tremendous amount of potential outside and inside the home. With creative landscaping that is both beautiful and functional, a tremendous amount of water can be saved. Our water is precious and we can capture rainfall when and where it lands and apply it during those times when it does not rain or use it in a totally new way. As Texas' population grows we will have to become more conscious of ways to conserve water. Capturing rainwater is one tool in this process.

INCENTIVES

The State of Texas encourages rainwater harvesting by eliminating the sales tax on collection system supplies. Also a number of counties and cities have either waved permitting fees, offered rebates on tanks, waived property taxes, provided rain barrels, irrigation audits, low flow toilets and/or set up demonstration sites to help encourage and educate the public on the need to conserve this precious commodity. Check with your local governing bodies for more information and check out these websites for contact information and upcoming activities.

SOURCES OF INFORMATION

Websites

American Rainwater Catchment Systems Association http://arcsa.com

Texas AgriLife Extension Service Rainwater Harvesting http://rainwaterharvesting.tamu.edu/

The Texas Water Development Board http://www.twdb.state.tx.us

Texas Commission on Environmental Quality http://www.tceq.state.tx.us

Author Index