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Modeling Phytophthora disease development in chile and bell peppers under rain feed and irrigated conditions.

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Abstract

Different forms of phytophthora attack different plant species, but the abiotic and biotic factors that determine the virulence of disease are similar for all type of phytophthora blight. *Phytophthora capsici* is a major disease that leads to large financial loss on chile peppers, bell peppers, and cucurbit crops in the United States, including tomatoes, cucumber, watermelon, squash, and pumpkin. Oospores provide the initial source of inoculums in the field, and multiple life cycles in a growing season occur through improper irrigation management. The research objective was to develop a conceptual model of the life cycle of *phytophthora capsici* and the disease development on chile and bell peppers as affected by soil temperature and wet/dry soil moisture cycles caused by irrigation or rainfall events. A simple life cycle model, which describes the relationship between host and pathogen population density throughout the growing season and overwinter developed by Thrall, was combined with an irrigation scheduling model for one-dimensional and two-dimensional flow that predicted the incidence development of chile and bell peppers grown in New Mexico and North Carolina that were furrow or drip irrigated. The model and measured phytophthora disease incidence on chile peppers grown in Las Cruces, NM, under alternate-row furrow irrigation was 55% at the end of the growing season. The model predicted a disease incidence of 5% compared to a measured disease incidence of 1.5% for trickle-irrigated chile. The *phytophthora capsici* disease incidence of drip-irrigated bell peppers at Clayton, NC, in 1998 when only two irrigations were applied in addition to rainfall, was measured at 55% compared to the modeled 52% disease incidence. The model predicts accurately the disease development rate of *phytophthora capsici* under low rainfall in Las Cruces and high rainfall in Clayton for both trickle and furrow irrigation if the appropriate one- or two-dimension water flow model is used in the simulation.

Introduction

Phytophthora blight is caused by the oomycete pathogen. Different forms of phytophthora attack different plant species, but the abiotic and biotic factors that determine the disease virulence are similar for all types of phytophthora blight. *Phytophthora capsici* is a major disease that leads to large financial loss on crops of chile peppers, bell peppers, and cucurbit in the United States, including tomatoes, cucumber, watermelon, squash, and pumpkin (Hwang et al., 1995, Kreutzer et al., 1940, Ramsey et al., 1960, Yan Maa et al., 2008, & Babadoost, 2000). Sanogo and Carpenter (2006) have shown all the commercial chile pepper (Capsicum annuum) fields in New Mexico are infected to various degrees, mostly with *phytophthora capsici*. Chile pepper is grown on approximately 1.3 million hectares in China, and *phytophthora capsici* has been reported to infect about 20% to 30% of the conventional farmed chile fields (Yan Maa et al., 2008).

Phytophthora capsici is a heterothallic organism in which two compatibility types designated A1 and A2 are needed for sexual reproduction. The sexual structure oospores are the main survival propagule and primary source of inoculums in the field (Bowers, 1983). Oospores provide the initial source of inoculums in the field, and multiple life cycles in a growing season occur through improper irrigation management (Bowers et al, 1990, Ristaino , 1990, Ristaino ,1991, Schlub, 1983). The virulence of the disease also is caused by the concentration of the pathogen in the soil at the beginning of the growing season. Because the pathogen is present in most soils, the overwintering survival rate also affects the virulence of the pathogen. In chile peppers, the phytophthora disease affects roots, crowns, stems, leaves, and fruit, causing seedling damping-off, stem lesion, stem and leaf blight, and fruit rot (Shannon, 1989, Biles et al., 1995). In spring, the oospores germinate into mycelium, which produces sporangia in water-saturated soil. Zoospores released from the sporangia swim through wet soil toward roots, where they encyst, germinate, and infect the root, causing it to rot. Secondary sporangia are produced on the infected root surface, and more zoospores are released. Oospores inside the rotting roots survive over winter. Zoospores and sporangia also may be splashed up onto plant leaves during rain or irrigation. Infected leaves produce additional sporangia, which release zoospores, which can be splashed onto adjacent plants or moved throughout the field on contaminated equipment. Consequently, during the growing season, the initial concentration of zoospores may be low and insufficient to kill a plant. The root and crown rot phase of the disease initially can appear on plants early in the growing season in areas of the field where soil remains saturated with water after an irrigation or rainfall. Subsequent periods of soil saturation encourage further disease development and plant death (Matheron and Porchas, 2002).

The life cycle of *phytophthora capsici* requires a wet/dry cycle, but the disease development also is affected by soil temperature. Rainfall and periodic furrow irrigation usually provide the needed wet/dry cycle in the soil, favoring sporangia formation during the drying period and zoospore release during flooding (Bowers and Mitchell, 1990).

Currently, best management practices (BMP) for control of the disease includes field preparation where fields are well drained with no low-lying areas that collect water (Larkin et al., 1995). Because phytophthora blight usually develops in fields in low-lying areas (Ristaino et al., 1993), laser leveling can be used before planting to minimize areas of standing water. The field also can be subsoiled or chisel-plowed to improve drainage in compacted areas (Garrison, 1999). Irrigation management should include reducing the number of wet/dry cycles though proper timing of irrigation both from flood, drip, and sprinkler irrigation. Disease incidence and severity are more severe and onset occurs earlier with more frequent than with less frequent irrigations (Café-Filho et al., 1995, Café-Filho et al., 1995, & Ristaino, 1991). A less frequent irrigation schedule on peppers of 21 days versus seven days resulted in less phytophthora blight without a reduction in yield (Café-Filho and Duniway, 1995). Drip irrigation on a daily basis prevents the occurrence of this wet/dry cycle and consequently controls the development of the disease (Xie et al., 1999). Alternate furrow irrigations are a BMP that can reduce the incidence of phytophthora root rot, reducing inoculum spread and disease in pepper (Biles et al., 1992, & Daniell and Falk, 1994).

The level of phytophthora in the soil can be determined only by taking a soil sample, culturing the sample and counting the number of propagules on the incubation plate per gram of oven-dried soil (McCain et al., 1967). If initial concentrations are low in a field at the beginning of a growing season, then proper irrigation management is not as critical as when the concentrations are high and can lead to 50% or more loss of crop yield. Control of phytophthora disease requires a multifaceted approach that integrates irrigation management, cultural practices, and non-chemical treatments

(Erwin and Ribeiro, 1996, Perez et al., 2003, & Mojica-Marín et al., 2011). Such a complicated system can be can be evaluated only through a modeling approach.

The objective of the research was to develop a conceptual model of the life cycle of *phytophthora capsici* and the disease development on chile and bell peppers as affected by soil temperature and wet/dry soil moisture cycles caused by irrigation or rainfall events. The second objective was to evaluate the model in different environmental conditions to determine the robustness of the model to predict the *phytophthora capsici* disease development rate for these two plant types.

Model description

Thrall et al. (1997) presented a simple life cycle model for phytophthora. The model describes the relationship between host and pathogen population density throughout the growing season, and over winter, for both natural and agricultural systems. Modeling of the life cycle of the host and pathogen provides insight and guidance on how to manage the pathogen to minimize yield loss. Soil water budgets and irrigation scheduling models (Sammis, et al., 2012, Ben-Asher et al., 1986) are available to model the remaining variables that affect the intensity and timing during the life cycles of phytophthora (Figure 1).

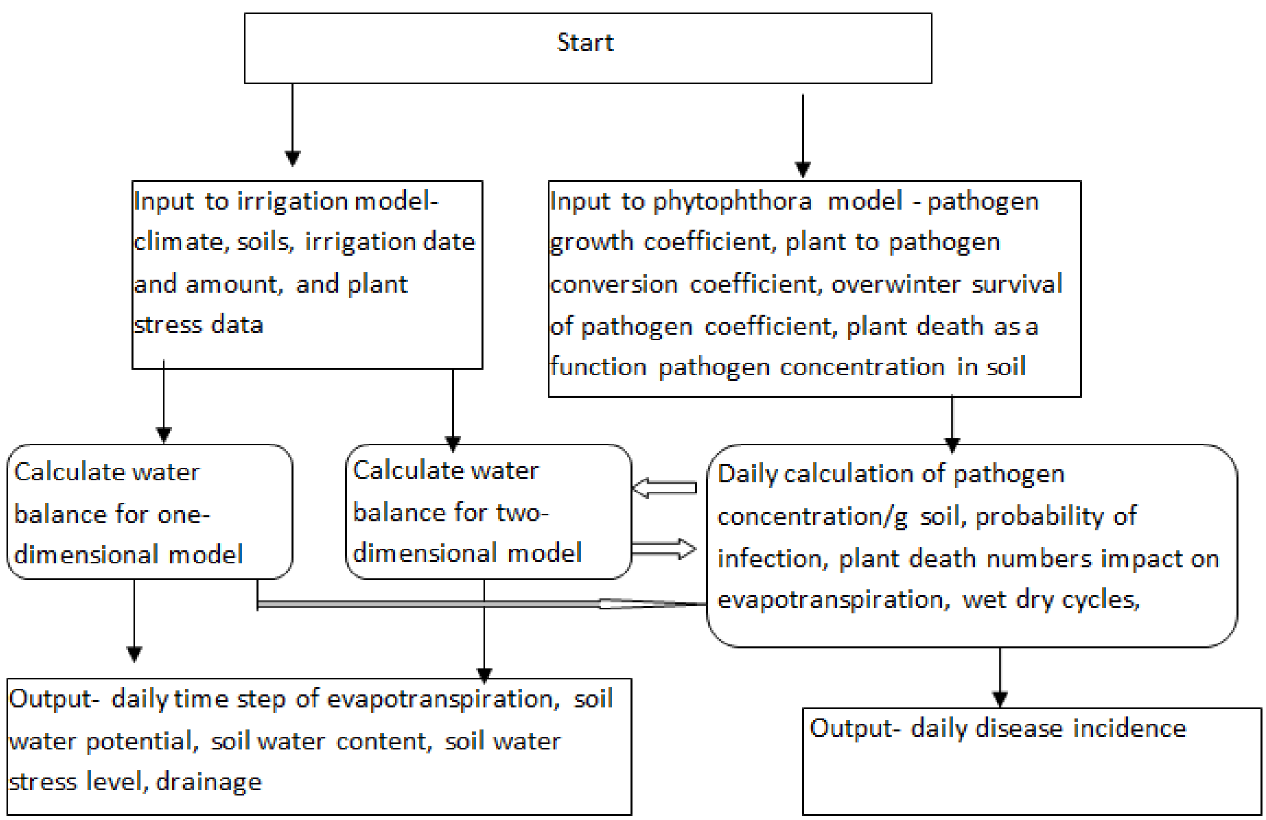

Figure 1. Block diagram of model

The model of Thrall et al. (1997) assumes that in temperate climates, population growth of soil-borne fungi occurs during summer months (through saprophytic growth and spore production, or through infection of new hosts), while during winter months, resting structures of chlamydospores can decay, but no new growth occurs. For the above species, oospores would be the resting structures considered. Consequently, the initial concentration of the pathogen population at the beginning of the growing season determines the initial virulence of the pathogen, along with the plant density of the host. In the case of agriculture, the host population is constant from year to year, which is not the case in a natural system. Overwinter survival of the pathogen depends on soil temperature but is generally considered to be 10% of the fall concentration. In Thrall et al.'s (1997) model, the time step (t) of the model is dependent on the time step for the birth rate of the pathogen, which can be daily or seasonal or any time increment where the plant population change affects the concentration of the pathogen. If the time step is set to daily, then the time step for phytophthora can be determined from an agricultural water balance model set up for the specified host crop. The soil-water potential is calculated daily, and when an irrigation or rainfall event occurs that wets and then dries the soil past threshold values, a time step is implemented in the Thrall et al.'s model. This assumes that during the days when the soil is drying out but a wet/dry cycle does not occur, the concentration of phytophthora zoospores in the soil does not occur by the released of new zoospores by sporangia (Café-Filho et al., 1995, Ristaino, 1991, & Xie et al., 1999).

The Thrall et al. (1997) model is described by Equation 1 (labeled Equation 2 in paper):

$$Y(t+1) = Y(t)\alpha(1+\mathring{y}-\int Y(t)) + \alpha\, \varepsilon\, X(t)\, P \quad (1)$$

Where: P is the total probability of infection, $P = 1- e^{-BY(t).}$

t = daily time step of model Y(t+1) changes only when a wet/dry cycle has occurred.

Y= concentration of pathogen in the soil.

α= overwinter survival rate of the pathogen in the soil.

$\mathring{y}$= host independent birth rate of soil pathogens that can live as sprophytes.

$\int$= strength of pathogen-dependent effects on the pathogen birth rate.

ε= rate at which infected plants are converted to the pathogen component in the soil.

X= plant population.

B= disease transmission coefficient.

The probability of infection (P) is described by an exponential function (Equation 2) or a linear function (Equation 3).

$$P= 1- e^{-BY(t)} \quad (2)$$

$$P= B_1\, Y(t) \quad (3)$$

Where Y(t) is the infection concentration pathogens/g soil (pgs) from Equation 1.

B= exponential transmission parameter, which is a measure of transmission efficiency.

B_1 = linear transmission parameter, which is a measure of transmission efficiency.

In agriculture, the plant population (X) is described by Equation 4:

$$X(t+1)= X(t)\,(1- \text{Loss}\, Y(t)\, P) \quad (4)$$

Where: X = the population of plant /area.

Loss= death of plant caused by concentration of disease organism.

A one-dimensional irrigation scheduling model for furrow and sprinkle irrigation and a two-dimensional model describing water movement under drip irrigation were combined with the Thrall model. The one-dimensional irrigation scheduling model is a simple volume-water budget model that solves the water balance equation on a daily time step after Sammis, et al. (2012).

The volume balance equation is:

$$\Delta Sm = R + I - Et - D \quad (5)$$

where R = rainfall (mm)

I = irrigation (mm)

D = drainage (mm)

Et = evapotranspiration (mm)
ΔSm = change in soil moisture (mm).

$$Et = Et_o \times Kc \times f \qquad (6)$$

Et_o is calculated using penman's reference evapotranspiration equation described by Allen et al. (1998) when the full climate data is available and Et_o is calculated using Hargreaves and Samani (1985) equation when only temperature data is available.

The crop coefficient (Kc) is a fourth order polynomial where:

$$Kc = a + b*GDD + c*GDD^2 + d*GDD^3 + e*GDD^4 \qquad (7)$$

Where: GDD is growing degree days.
Growing-degree days were calculated as:

$$GDD = \frac{(T_{max} + T_{min})}{2} - T_b \qquad (8)$$

Where: T_{max} = daily maximum temperature (°C).
T_{min} = daily minimum temperature (°C).
T_b = base temperature (°C)

If T_{max} exceeds a cutoff temperature, then T_{max} is set to that cutoff temperature. The same occurs for the T_{min} minimum temperature. The cutoff temperatures are inputs to the model along with the base temperature, and the values depend on the crop being grown. The cutoff temperatures and crop coefficients for chile peppers, which also were used for bell peppers, are presented by Saddiq (1983).

The f factor is a soil water stress linear function (0-1) and usually is described as a step function where f is set to 1 when the soil water is at field capacity or larger and then decreases linearly when the soil water decreases below a threshold value (Allen et al., 1988).

The irrigation scheduling one-dimensional model has a single soil layer equal to the depth of the roots that changes throughout the growing season as a function of growing degree days (GDD). Consequently, it has no root extraction pattern. The two dimensional irrigation scheduling model is an ellipsoid layered model with a root extraction patter for each ellipsoid. Sammis et al. (2012) describes the comparison between the two models. Inputs to the model are climate, soil water hold characteristics, and irrigation data (Table 1). The model is run from planting date to harvest date. The climate data to calculate reference evapotranspiration (E_{to}) for grass was obtained from nearby weather station data. Irrigation or rainfall water is applied, increasing the available soil water in the root zone. The model automatically applies an irrigation when the soil water depletion reaches a input value in the model. Setting the value to 0.99 prevents the model from automatically irrigating and only the applied water on the specified data an input to the model simulated. Water application in excess of the soil water holding capacity of the root zone goes to deep drainage (Equation 5).

Table 1. Chile and bell peppers disease model parameters

Parameter	Values	
Soil water submodel	Chile Peppers	Bell Peppers
Beginning root depth, cm	10	10

Maximum root depth, cm	107	107
Root growth coefficient, cm/growing degree day	0.028	0.028
Irrigation amount for computer applied irrigation, cm	0.2	0.2
Soil water holding capacity between field capacity and permanent wilting point, cm/cm	0.12	0.12
Soil water management allowed depletion, %[1]	99	99
Row spacing (two-dimension model), cm	107	107
Water hold capacity of soil below permanent wilting point, cm/cm	0.1	0.1
Growing degree day coefficients for crop Coefficient calculation constant for GDD in degree C		
Equation 7 a=	0.098	0.098
Equation 7 b=	5.994 E-5	5.994 E-5
Equation 7 c=	6.188 E-7	6.188 E-7
Equation 7 d=	-1.895 E-10	-1.895 E-10
Cutoff temperature		
Tmax =	30	30
Tmin =	5	5
Tb =	5	5
Slope of water stress function ("f" in Equation 6)	2	2
Intercept of water stress function ("f" in Equation 6)	0	0
Disease submodel		
Initial pathogen, pgs one-dimensional model	45 two-dimensional model	10 on 6/13/1988
two-dimensional model	30 two-dimensional model	40 initial 1989
Cutoff temperature for zoospoor, degree C	35	35
Rate of growth of pathogen, pgs	0.03	0.03
Rate of plant converted to pathogen, pgs/plant	0.01	0.01
Strength of density on pathogen birth rate , pgr	-0.89	-0.89
Overwinter survival rate of pathogen in soil	0.1	0.1
Beta	0.0005	0.0005
Loss plant /pgs	0.05	0.05
Temperature submodel		
Soil albedo, decimal	0.15	0.15
Average annual air temp., C	16.2	15.5
Annual amplitude in mean monthly temp, C	22.2	16.6
Mean bulk density of soil, g/cm^3	1.4	1.4

A detailed description of both the one-dimensional and two dimensional model is presented by Sammis et al. 2012.

Because irrigation wet/dry cycles can be controlled by converting the irrigation from a furrow system to a drip irrigation system, it is necessary to combine the phytopathology model with a two-dimension volume balance trickle irrigation model that is based on the ellipsoid model described by Ben-Asher et al. (1986) and Sammis et al. (2012). The row distance between line sources and corresponding soil depth are divided into five halves of ellipsoids, and the ellipsoid shape is determined by the ratio of x/y (major/minor axis), an input to the model ranging from 0.5 to 1 (Figure 2). The x is in the root depth direction. This value is based on the soil type as defined by the soil water holding capacity of the soil, which is an input to the model. Rainfall is applied to the surface of each ellipsoid based on the surface of each ellipsoid containing 20% of the row spacing. All the rainfall stays within the ellipsoid that it enters except for that amount that exceeds the water required to bring the ellipsoid to field capacity. This water then is moved to the next ellipsoid and is distributed evenly throughout the ellipsoid. The extraction percentage of evapotranspiration (Et) taken from each ellipsoid depends on the root development depth. Root growth rate is calculated in the x direction, and when the roots reach the next ellipsoid, the Et extraction is distributed from the first to the rooting depth ellipsoid. Details about the two-dimensional model and a comparison between the one- and two-dimensional models for scheduling irrigation using a drip irrigation system is presented by Sammis et al. (2012).

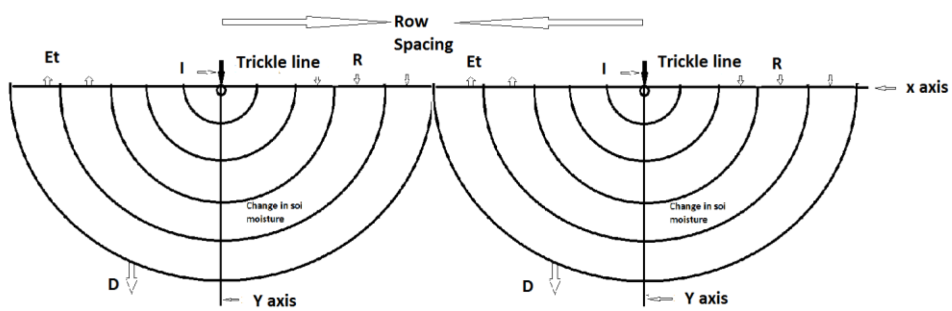

Figure 2. A two-dimensional volume balance water model.

Material and Methods.

Chile Pepper Experiment

The combined host-pathogen irrigation model for *phytophthora capsici* disease incidence on chile was tested against a *phytophthora capsici* disease development experiment conducted in 1995 on Brazito sandy loam soil (mixed, thermic typic torripsamments) located at the Fabian Garcia Agricultural Research Center in Las Cruces and on a bell peppers experiment conducted at Clayton reported by Ristaino (1991) and Ristaino and Hord (1992). The experimental design at Las Cruces was a randomized complete block design with three irrigation levels (daily trickle irrigation, three-day trickle irrigation, and alternate row furrow irrigation) and two phytophthora levels (non-infected [control] and infected). The daily trickle irrigation experiment was not used to evaluate the irrigation disease model because this high irrigation frequency is not used by growers. The experiment was conducted in 1995. Every row was furrow-irrigated during transplant establishment and switched to alternate row furrow irrigation thereafter.

The 6143 strain, A1 compatibility type of *phytophthora capsici* isolated from diseased chile plants was used for this study. The inoculums were obtained by growing the isolate in vermiculite media amended with 350 ml of V8 broth and incubated at 24 C for four weeks (Ristaino et al., 1992). In April 1995, the inoculums, containing mycelium and sporangia, were placed on both sides of the bed, 15 cm from the center and 5 cm deep, at a rate of 360 ml m^{-1}.

Chile seedlings-- *capsicum annum* New Mexico 6-4, were transplanted on April 24, 1995, after eight weeks of growth in a greenhouse. The plants were placed on both sides of the bed in a staggered arrangement. Plants were placed 7.5 cm from the center with 60 cm spacing between two adjacent plants on the same side and 30.5 cm between two adjacent plants on opposite sides of the bed.

T-tape (T-tape: TSX-508-08-670, T-Systems, San Diego, CA) with emitters every 20 cm was buried 20 cm below the soil surface and in the center line between plant rows. The flow rate of the system was 5.0 l hr^{-1} m^{-1}. The drip system was operated by a computer-scheduling model that applied water to satisfy the calculated Et with 20% excess water applied based on an irrigation application efficiency of 80%. The water was applied to plots three times a week, and the amount was calculated from the accumulated Et since the previous irrigation. The water applied was measured with a flow meter. The experiment had an average 2.1 cm of water applied. The irrigation application depth varied from 0.15 cm, in the early part of the growing season, to a maximum application rate of 4.4 cm. The total number of irrigation applications was 56 in 1995. URAN® (32-0-0) was applied with the irrigation water for a total seasonal application of 397 kg ha^{-1} of NO_3-N. Before transplanting, phosphorus was applied at a rate of 67.3 kg ha^{-1}. Green yield was harvested on July 13, 1995, Aug. 2, 1995, on July 16, 1996, and Aug. 15, 1996, from three one-meter long subplots. Red chile yield was harvested on Oct. 15, 1995, and Oct. 31, 1996. Red chile and green chile yields were weighed and subsampled for moisture content. Combined yield (green chile yield plus red chile yield) was obtained by converting dry red chile yield to wet yield using a wet/dry ratio of eight (Gore and Wilken, 1995). Soil moisture was measured every two weeks with a neutron probe at depths of 30 cm, 60 cm, 90 cm, and 120 cm in the middle of the beds adjacent to the drip line.

Soil matric potential (ψ_m) was monitored weekly in three blocks at depths of 15 cm and 30 cm by tensiometers installed between two plants in the middle of the beds. Air temperature data was collected from a Campbell climate station at the site. Soil temperatures in 1996 were measured in three blocks using thermal couples located in the middle of the bed. The thermal couples were connected to a Campbell Cr10 datalogger, which recorded the temperature every 10 seconds and averaged the temperature hourly.

Disease incidence was collected weekly before June 14 i**n** 1995 and daily thereafter by visual examination. When the symptoms of disease progressed to the stem necrosis stage, the diseased plants were sampled for confirmation of the presence of *phytophthora capsici* by inoculating chile seedlings in the greenhouse. A complete description of the experimental design is given by Xie et al. (1999).

Bell Pepper Experiment.

An experiment on drip-irrigated bell peppers (variety Deystone Resistant Giant) artifically infested with *phytopthora capsic* was conducted by Ristaino (1991) and Ristaino and Hord (1992) in Clayton in 1988 and 1989. Plots were drip-irrigated two times during the 1988 growing season after being infected with three levels of inoculum and a control. The soil type was a Johns sand loam. The eight-week old pepper seedlings were transplanted in soil beds that had been treated with methyl bromide-chlorpicrin. The experimental design was a split block design with irrigation as main plots and densities of inoculum as supplots. The treatments were replicated four times. The plots were either uninfested or infestested 43days in 1988 and for 31 days in 1989 after transplanting. Inoculum of *phytophthora* capsicis in V8 vermiculite mediums as applied to subplots. The incidence and severity of the disease on shoots was evaluated visually during the growing season. Soil samples to evaluate moisture conten an phythopthora were taken from the 0-20 depth. A complete description of the experimental design is givn by Ristaino (1991) and Ristaino and Hord (1992), along with the results of the experiment of the disease development rate over time.

Results

The disease incidence predicted by the one-dimensional model for the alternate row furrow irrigation followed the measured data except early in the growing season where disease incidence development occurred sooner than predicted by the model (Figure 3).

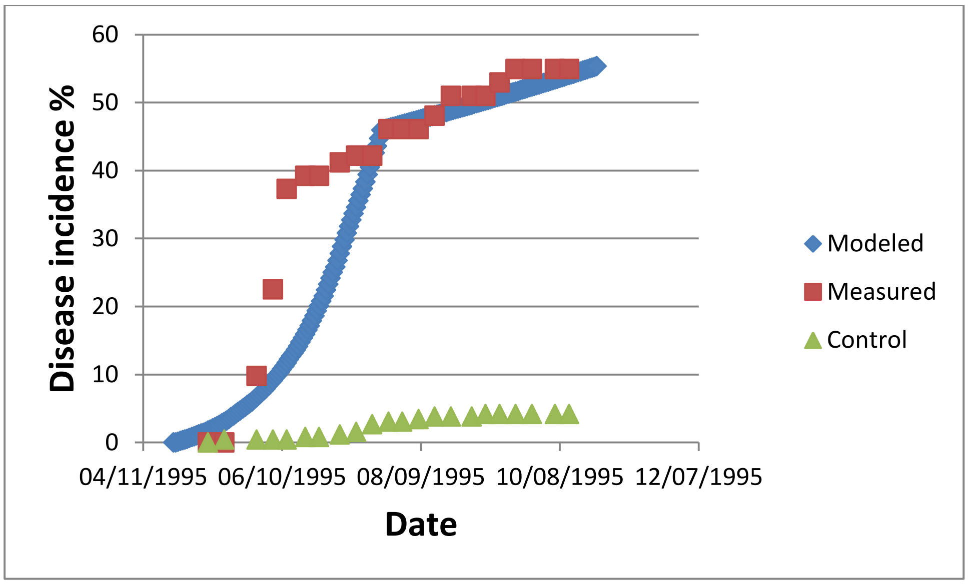

Figure 3. Measure and one-dimensional modeled disease incidence of phytophthora capsici for the furrow alternate row chile irrigation. The control was not infected with *Phytophthora capsici*.

The initial concentration in the soil was set in the model at 45 *phytophthora capsici* pathogen /g of soil. The level in the soil was not measured in the experiment after the application of inoculums, which is the case in most *phytophthora capsici* experiments. The model was modified to include the effect of high soil temperature on the life cycle of *phytophthora capsici*. If the soil temperature reached 30 C, then the disease incidence increase was described by a linear function that was a function of the *phytophthora capsici* levels in the soil at the time of the high temperature occurrence. The additional assumption added to the model is that the high soil temperature stopped the life cycle of the *phytophthora capsici*, and only those zoospores in the soil at that time continued to cause disease incidence. Without the additional constraint, the model predicted the disease incidence would continue in the power function shape that occurred in the beginning of the growing season. Because the data did not support this assumption, the additional temperature constraint was added to the model. The measured and modeled soil moisture content were similar indicating that the soil moisture balance component of the model was tracking the impact of irrigations on the number of wet dry cycles correctly (Figure 4)

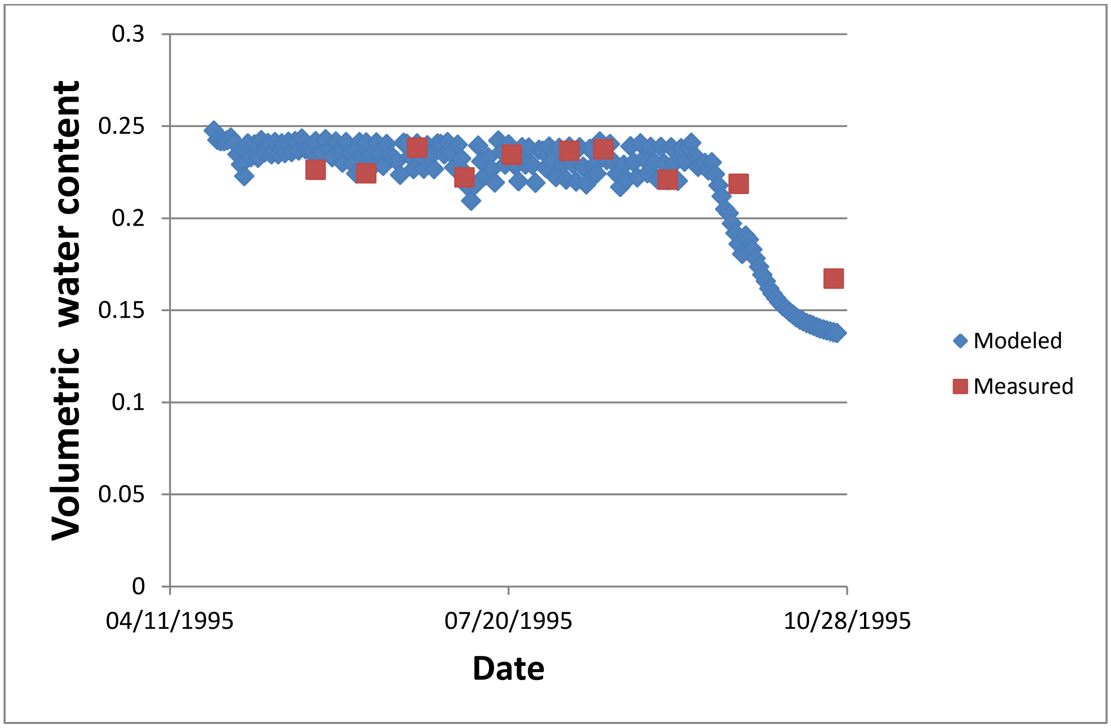

Figure 4. Measured and modeled (one-dimensional model) water content (30-90 cm) in a drip-irrigated chile field in Las Cruces, NM; 1995.

The model also was run using the two-dimension drip-irrigation model where the irrigation was applied every three days (Figure 5).

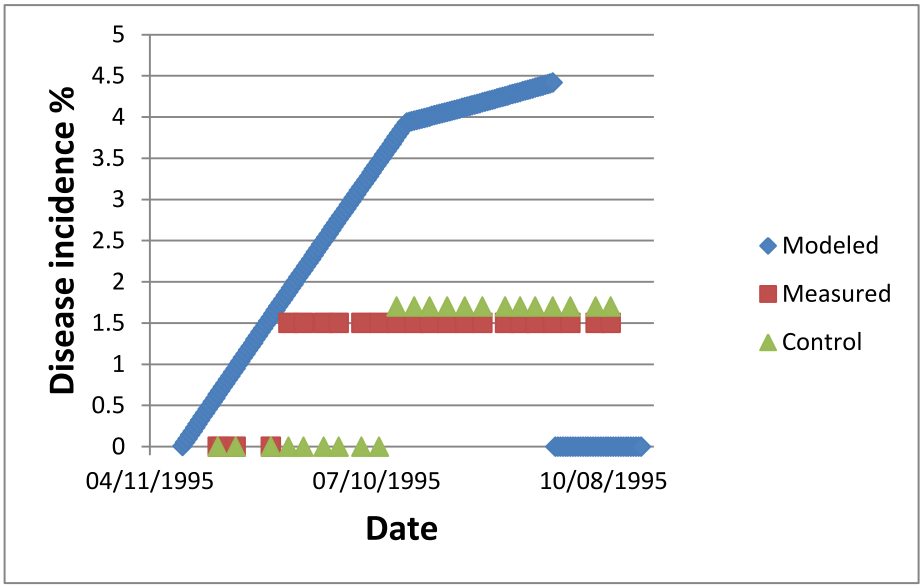

Figure 5. Measure and model disease incidence of phytophthora capsici for the 3 day trickle irrigation chile. The control was not infected with phytophthora capsici.

The two dimensional soil- water-disease- model overestimated the disease incidence final level for the three-day drip irrigation treatment. Something stopped the low rate of disease development after two months that is not explained by the model. However, the strength of the inoculums in the soil and the depth of infection are in question because no measurements were taken of soil inoculum levels.

The model parameters are estimates presented by Thrall et al. (1997) from a literature search with a wide range in values in the literature for the parameters. Addition experiments must be conducted before confidence in the model parameters is sufficient to determine if the difference between measured and modeled values is a function of the model structure or the model parameter values. Also, the model is a simple model that may not describe the biology of *phytophthora capsici* completely. Knowledge is lacking of the concentrations of *phytophthora capsici* in the soil under different environment conditions and of *phytophthora capsici* concentration over time and depth in the soil at location within the root volume. A better understanding of the relationship between soil water potential spatial distribution and disease propagation is critical. However, the model did simulate the interaction *of phytophthora capsici* with wet/dry cycles of soil moisture and the effect of soil temperature on *phytophthora capsici* disease development.

The model prediction of *phytophthora capsici* disease incidence was also compared to measurements of the disease incidence on bell pepper reported by Ristaino et al. (1991) where bell peppers in North Carolina were treated with *phytophthora capsici* at selected concentrations under a different drip-irrigation treatment, but where the majority of the water came from rainfall events. Two irrigations of 1.5 mm were applied 46 and 62 days after planting. The inoculum was applied 42 days after planting.

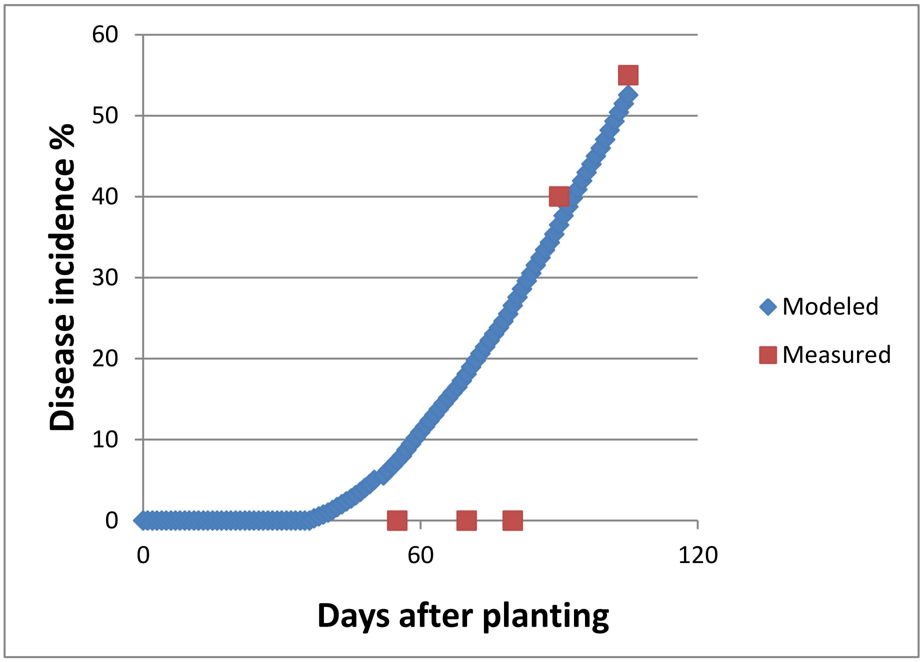

Figure 6. Comparison of model and measure *phytophthora capsici* disease incidence of drip-irrigated bell peppers at Clayton, NC, in 1988 when only two irrigations were applied in addition to rainfall and high disease inoculum.

The model disease incidence and model inoculum density (Figure 6 and 7) continued to rise as the growing season progressed. The disease incidence measurements along with inoculum density were steady during the growing season until the last measurements where both increased. The model predicted that the rainfall events would cause an increase in the disease which the measurements did not support. Consequently, soil microorganisms competition may have be suppressing the growth of the *phytophthora capsici*. This competition component is not in the model and may be more of a controlling factor in the higher rainfall area of NC. The organic matter in these soils is higher than in the soils in the west and higher organic matter soils have a higher diversity of microorganism (Linderman, et al., 1983).

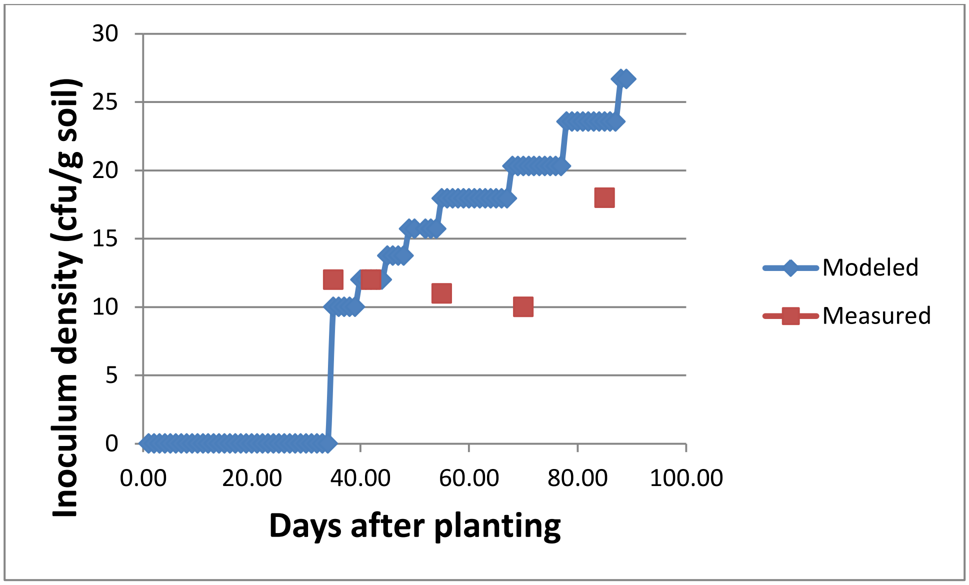

Figure 7. Measured and modeled inoculum density of phytophthora *capsici* the soil for drip irrigated bell peppers at Clayton, NC in 1988 with only two irrigations were applied in addition to rainfall and high disease inoculum.

In 1989 when the experiment was repeated but with a larger number of irrigations (six irrigations) the model followed the disease incidence measurements (Figure 8), but the measurements of the inoculum density of *phytophthora capsici* decreased over the growing season even though the disease incidence increased (Figure 9). The model predicted an increase in the inoculum density because in the model, the disease incidence is a direct function of the inoculum density. No error bars were given in the reported data but the variability of the inoculum density measurements determined by measuring the colonies of *phytophthora capsici* grown from a soil water agar extract on Masago's medium could be high. Also the inoculum density calculations did not include any measurements of chlamydospores in the root tissue which could have contributed to plant death.

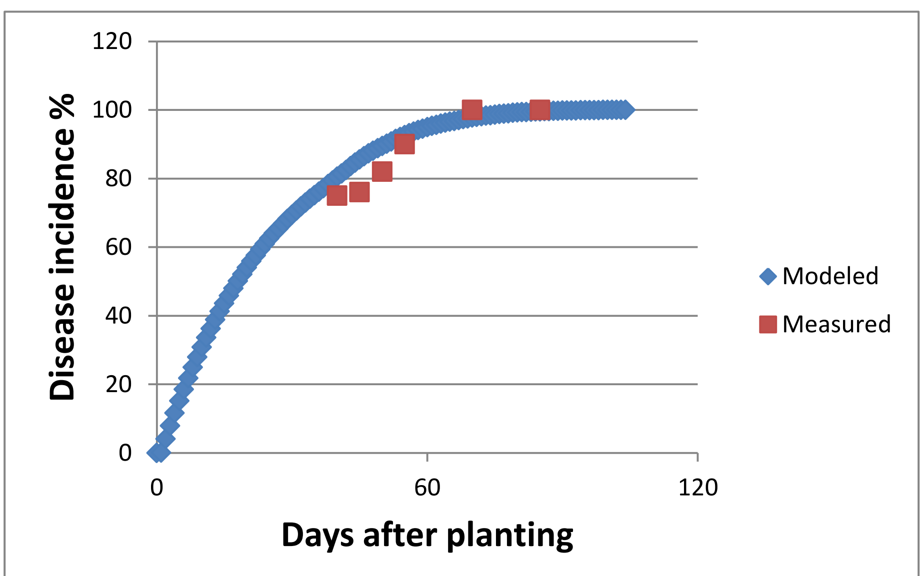

Figure 8. Comparison of model and measure *phytophthora capsici* disease incidence of drip-irrigated bell peppers at Clayton, NC, in 1989 when only six irrigations were applied in addition to rainfall and high disease inoculum.

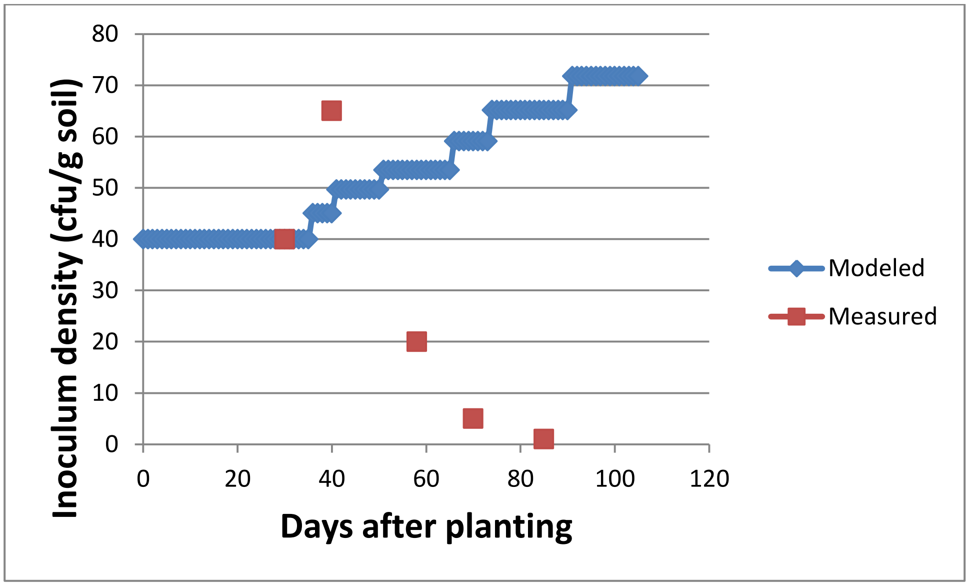

Figure 9. Measured and modeled inoculum density of *phytophthora capsici* the soil for drip irrigated bell peppers at Clayton, NC in 1989 with only six irrigations were applied in addition to rainfall and high disease inoculum.

The model and measured soil moisture for the two dimension soil water-plant-disease model had the same change in soil moisture throughout the growing season but the modeled over predicted the moisture content by 5 % compared to the measured values (Figure 10). This was similar to the results reported by Sammis et al. (2012) when comparing the modeled two dimension soil water content values averaged over an ellipsoid compared to point measurements from a soil core.

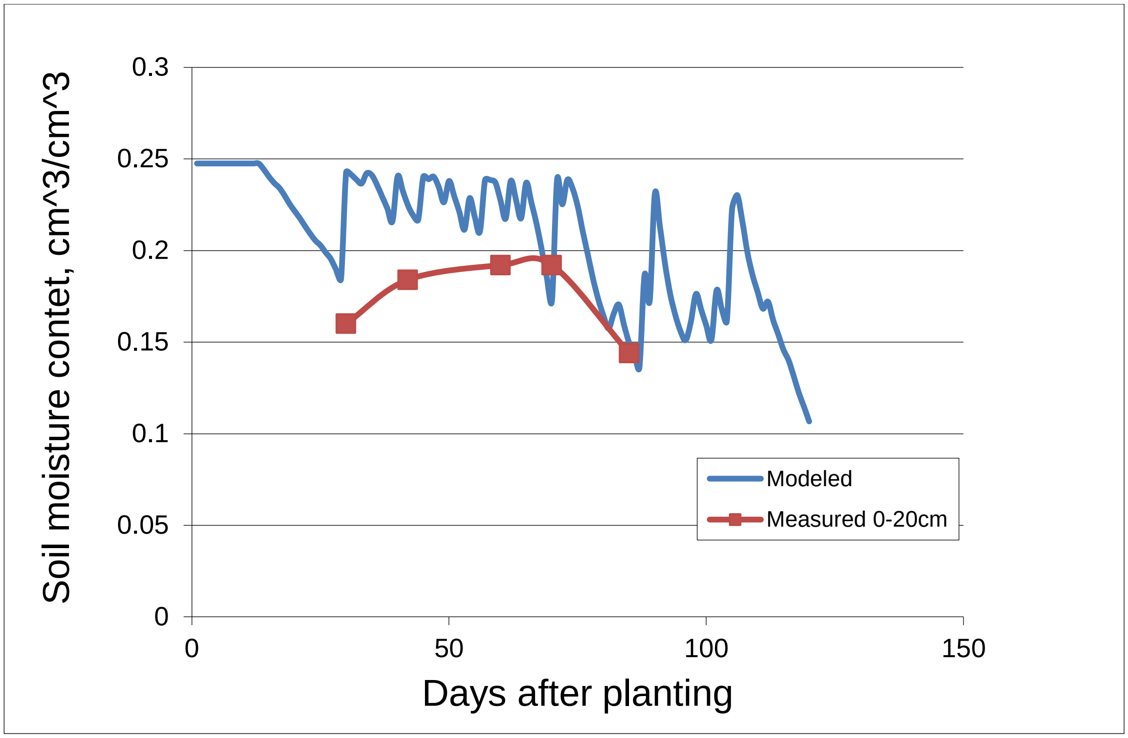

Figure 10. Measured and modeled two dimensional soil moisture content for drip irrigated bell peppers at Clayton, NC in 1989 with six irrigations in addition to rainfall and high disease inoculum. Model soil moisture is the second ellipsoid representing the soil moisture 21-42 cm location from the bell pepper row.

Conclusions

The chile pepper and bell pepper one-dimensional and two-dimensional irrigation scheduling models coupled to a *phytophthora capsici* disease model describe the progression of the disease under furrow irrigation, drip irrigation and drip irrigation, with rainfall supplying most of the water requirements of the crop. The model simulation of the *phytophthora capsici* disease progression points out the need for additional experiments where the *phytophthora capsici* concentration in the soil is measured along with the above-ground disease progression. Overwintering survival has a large impact on the model simulation and this was not measured. The values of the parameters in the model were estimates from the literature containing a large variation in numbers and these values need to be refined through additional field experiments because in some cases the parameter numbers were merely best guess values.

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Evaluation of Compensated Root Water Uptake Pattern of Greenhouse Drip Irrigated Chile

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Abstract
We evaluated comparative effects of the compensated (under water stress conditions using drip-irrigated partial root zone drying (PRD) techniques) and non-compensated (no water stress) root water uptake pattern of chile plants (NuMex Joe Parker; *Capsicum annuum*). The greenhouse pot experiments were conducted with three drip irrigation treatments: (1) control or non-compensated (fully irrigated), (2) PRD using vertically split-root system where the top 37% of the root zone system was exposed to water stress, and (3) PRD using two-compartment or lateral split-root system with alternately wetting and drying to impose water stress in the lateral part of the root zone. Results suggest that chile plants under these two drip-irrigated PRD treatments could compensate for water stress in one part of the vertical or lateral root zone profile by taking up water from less water–stressed parts of the vertical or lateral root zone regions, without affecting transpiration or photosynthetic rates to meet peak water demand. No significant differences were noted in the root length distributions and plant heights between PRD treatments and control. Either of the two drip-irrigated PRD techniques has a great potential to be adopted as water saving practices in chile production especially for environments with limited water.

Introduction

Water stress is one of the most critical factors that can decrease crop productivity across arid and semi-arid agricultural areas of New Mexico and the southwestern US. Water stress is exacerbated in these areas as a result of low rainfall, high evapotranspiration, and limited availability of irrigation water. However, a compensation mechanism within the crop root zone that balances reduced water uptake from one part of the rhizosphere by increased uptake in another less-stressed region of the root zone, while decreasing the loss of water due to evaporation can be beneficial for managing efficient use of irrigation water (Deb et al., 2011a). Partial root zone drying (PRD) is a potential water saving irrigation strategy where at each irrigation only a part of the rhizosphere is wetted with the remaining part left to dry to impose soil water stress. Although the hydraulic lift concept was proposed by Gardner in 1960, yet, there is still limited experimental evidence that plants under PRD can compensate for water stress in one part of the root zone by taking up available water from other parts of the root zone. In particular, the question remains unresolved whether chile plants under drip-irrigated PRD can compensate for water stress in one part of the root zone by taking up water from less-stressed parts of the root zone. The objective was to evaluate comparative effects of the compensated (under drip-irrigated PRD) and control or uncompensated (no water stress, fully irrigated) root water uptake pattern (or transpiration rate) of greenhouse drip irrigated chile plants. We hypothesized that (1) the response of chile plants to soil water stress compensation mechanism can be characterized from the drip-irrigated PRD experiments, and (2) compensated transpiration rate and plant growth under PRD will be similar to or greater than those without compensation.

Materials and methods

Experimental setup and irrigation treatments

The PRD experiment was carried out on chile plants in a greenhouse at New Mexico State University Fabian Garcia Science Center (latitude 32° 16′ 48″ N, longitude 106° 45′ 18″ W, elevation 1185 m). Seeds of New Mexican pod type chile (NuMex *Joe E. Parker*; *Capsicum annuum* L.) were sown in germinating tray until the appearance of the fifth leaf. At that stage, on 13 June 2011, chile plants were transplanted to pots (29 cm diameter and 54 cm deep), containing a 1:1:2 (v/v) mixture of sand: soil: organic matter (hereafter referred to as the soil), to produce a split-root system. Loading and compaction of soil in the pot was manually performed in 5-cm incremental layers to obtain a homogeneous profile. Experimental design consisted of a drip irrigation system, with two drip emitters per pot each emitting about 2 L h^{-1}. The drip tubing with the emitter was connected to the drip mainline tubing, which delivered water from a PVC water reservoir tank to the emitter tubing. The pumping system of the water tank provided a stable pressure to avoid variations in flow rate, and steady water flow rate was maintained through the flow control system. The bottom of each pot was perforated and covered with loosely woven fabric to allow free drainage without soil loss.

For each pot, the chile was irrigated every day at 800 h for 30 min during the period from 14 June (2DAT; 2 days after transplanting) to 31 October (142 DAT) 2011. The experiment was performed by applying three drip irrigation treatments with three replications per treatment: (1) control or non-compensation treatment was irrigated with two drip emitters placed at the pot surface. (2) PRD or compensation treatment (PRD_{vert}) in which the root zone was vertically divided into two parts (vertically split-root system) with two subsurface drip emitters placed at 20 cm depth, i.e., the top 37% of the root system was exposed to soil drying (or water stress), and the remaining 63% irrigated with subsurface drip emitters, and (3) PRD or compensation treatment (PRD_{compt}) in which the root zone was divided into two-compartment split-root system, in which roots were evenly separated into two compartments with a divider such that water exchange between two compartments was prevented. Plants were irrigated alternately on the two compartments with a drip emitter placed at the soil surface, and irrigation was switched between the two compartments at two-week intervals. Additionally three pots per treatment were used for monthly root distribution observation. All plants were fertilized with slow-release fertilizer [Scotts Osmocote Classic 14% Nitrogen (N)–14% Phosphate (P_2O_5)–14% Soluble Potash (K_2O)].

Determination of soil properties

Prior to transplanting, soil physical properties were determined using standard laboratory methods (Dane and Topp, 2002). The mean bulk density and saturated hydraulic conductivity (K_s) of the soil-mix were 1.34±0.05 Mg m^{-3} and 0.18±0.03 cm min^{-1}, respectively. Soil-mix water retention was determined on cores using the pressure chamber method at pressures (ψ) of 0, –300, –500, –1000, –3000, –5000, –10,000 and –15,000 cm H_2O (Fig. 1a). The field capacity (for $\psi \approx -300$ cm H_2O) and wilting point ($\approx -15{,}000$ cm H_2O) water contents were 0.41±0.024 and 0.28±0.02 cm^3 cm^{-3}, respectively. Soil-mix core samples were collected down to 40 cm soil depth to determine thermal conductivity using the KD2 probe (Decagon devices, Inc., Pullman, WA) at ψ of 0, –300, –500, –1000, –3000, –5000, –10,000 and –15,000 cm H_2O (Fig. 1b).

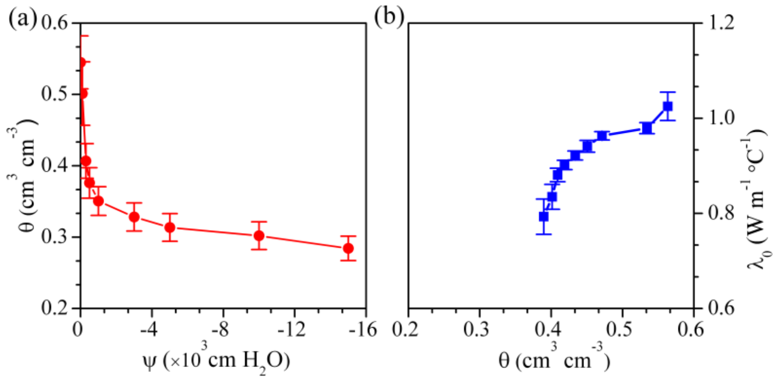

Fig. 1. (a) Water retention curve of the soil-mix (θ = volumetric water content and ψ = pressure head), and (b) thermal conductivity (λ_0) of the soil-mix as a function of the θ.

Measurement of soil water content, soil temperature, and microclimate

Two pots under each of the control and PRD_{vert} treatments were instrumented with two time domain reflectometry (TDR) sensors (CS640; Campbell Scientific, Inc., Logan, UT) and two temperature (TMC6–HD, Onset Computer Corp., Bourne, MA) sensors were installed at the depths of 5 and 25 cm to measure volumetric water content and soil temperature, respectively, at 10-min intervals. TDR and temperature sensors were installed at 5 cm on either compartment side of the PRD_{compt}.

Air temperature and relative humidity were measured using CS500 Temperature/Humidity sensors and net solar radiation using Q-7.1 Net Radiometer (Campbell Scientific, Inc., Logan, UT) inside the greenhouse. These measurements were made at 10–min intervals at 2 m above the soil surface of the greenhouse. To account for changes in evaporative demand inside the greenhouse, atmospheric vapor pressure deficit (VPD) values were calculated using Murray's equations (1967) using the hourly average air temperature and relative humidity data. The VPD outside the greenhouse were estimated using hourly average data obtained from Fabian Garcia Science Center weather station.

Measurement of plant photosynthetic and transpiration rates

Plant photosynthetic and transpiration rates and leaf temperature were measured between 700h and 900h on two fully expanded and exposed leaves per treatment. These measurements were made at two-week interval using LI-6400XT portable photosynthesis system (LI-COR Biosciences, Lincoln, NE).

Measurement of plant growth and root length density

Plant height was measured manually once every two weeks and canopy development was continuously monitored using garden cameras. Roots from control and treatment pots were manually washed and RLD distributions were determined four times during the period from 13 June to 31 Oct. 2011. Root images were acquired using EPSON V700 Photo Dual Lens System flatbed scanner (Epson America, Long Beach, CA). Following the procedure described by Deb et al. (2011b), analysis of the root length density (RLD) was performed with the WinRHIZO version 2008a (Regent Instruments Inc., Quebec, Canada).

Results and discussion

Soil water content and soil temperature

The trend and magnitudes of volumetric water content (θ) at 5 and 25 cm depths in the control were similar during a period from 2DAT to 142DAT, which varied between 0.34 and 0.47 cm^3 cm^{-3} at 5 cm, and 0.25 and 0.45 cm^3 cm^{-3} at 25 cm pot depth (Fig. 3a). As expected, the θ at 25 cm was consistently higher than that at 5 cm under PRD using vertically split-root system (PRD_{vert}) (Figs. 3b-c) because irrigation was applied with subsurface drip emitters placed at the 20 cm depth to impose water stress above 20 cm. For example, the θ varied from 0.25 to 0.38 cm^3 cm^{-3}, and 0.43 to 0.51 cm^3 cm^{-3} at 5 and 25 cm depths, respectively. The relatively higher values of θ could be explained by the water retention behavior and a much higher water holding capacity of the soil (Fig. 1a). The variations in θ at 5 cm under PRD_{vert} treatments (Figs. 2b-c) might be attributed to water extraction by roots above 20 cm depth. This also implies that water might be transported from the subsurface drip irrigation source at 20 cm to the surface (above 20 cm) by capillary rise. Either side of the two-compartment split-root system (PRD_{compt}) treatment had either a higher or a lower θ at 5 cm depending on whether it was being irrigated or not (Fig. 4a).

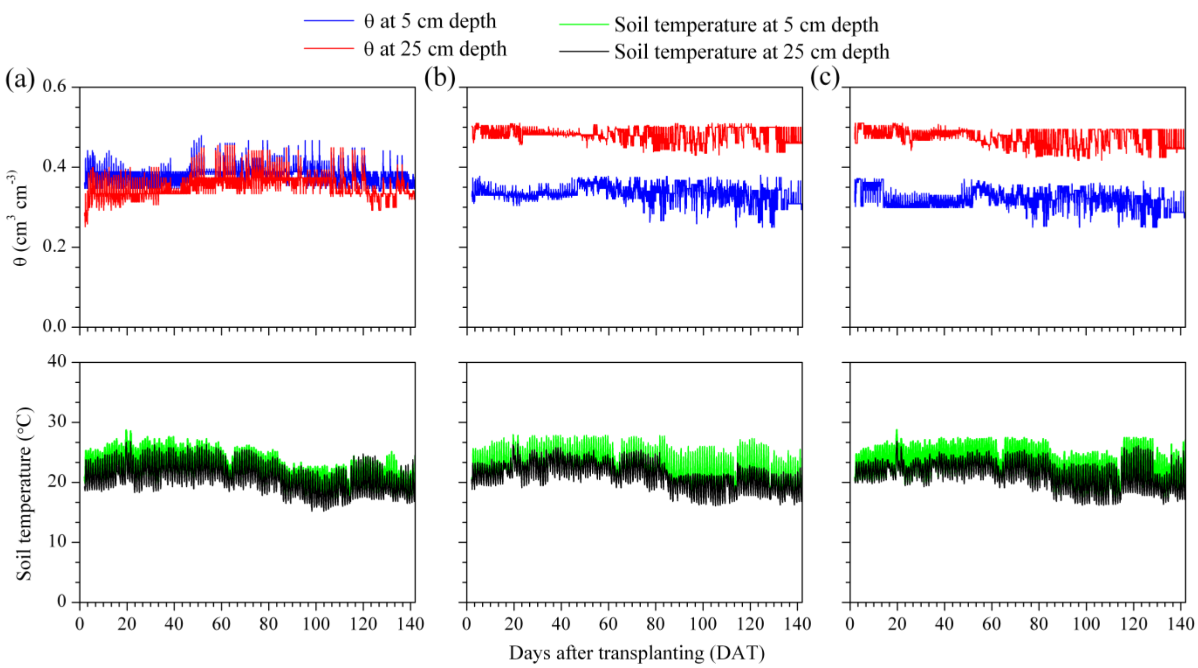

Fig. 3. Daily variations in volumetric water contents (θ) and soil temperatures at pot depths of 5 and 25 under (a) controls or non-compensation (no water stress, fully irrigated), and (b, c) drip-irrigated compensation or partial root zone drying (PRD) treatments using vertically split-root system (PRD_{vert}) during the period from 2 DAT (days after transplanting) to 142 DAT (14 June to 31 October, 2011).

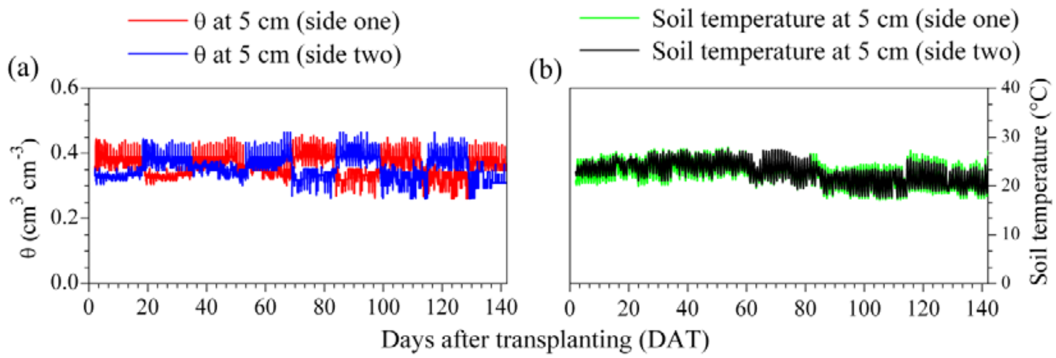

Fig. 4. Daily variations in (a) volumetric water contents (θ) and (b) soil temperatures at pot depth of 5 cm at each side of the drip-irrigated partial root zone drying treatment (PRD_{compt}) using two-compartment split-root system during the period from 2 DAT (days after transplanting) to 142 DAT (14 June to 31October, 2011).

Similar to temporal trends, magnitudes of soil temperatures at 5 and 25 cm pot depths did not noticeably vary among treatments (Figs. 3 and 4b). Soil temperatures at 5 and 25 cm depths in control and PRD_{vert} treatments (Fig. 3) showed a typical diurnal sinusoidal pattern, with decreasing amplitude with depth. Similar diurnal pattern was observed for soil temperatures at 5 cm depth for each side of the PRD_{compt} treatment (Fig. 4b).

Photosynthetic and transpiration rates and root length density

Photosynthetic and transpiration rates were unaffected by the applied irrigation treatments: control (Fig. 2a), PRD_{vert} and PRD_{compt} (Table 1). To meet the peak water demand, chile plants under both PRD treatments could compensate for water stress in one part of the vertical (PRD_{vert}) (above 20 cm depth; Fig. 2b-c) or lateral (PRD_{compt}) (Fig. 3a) root zone profile by taking up water from less-stressed (relatively higher θ) parts of the vertical or lateral root zone regions where water was available. During the period from 2DAT to 142DAT, the evaporative demand, expressed as atmospheric VPD inside the greenhouse (with climate control system), exhibited less fluctuation and was likely to be high (Fig. 5). For example, daily VPD values varied from 0.63 to 2.6 kPa inside the greenhouse compared with outside ones that varied from 0.52 to 3.5 kPa. The abrupt decrease in transpiration rates, particularly on 79DAT (Table 1), could be explained by the leaf temperature above that of the surrounding air. In general, leaf temperature was lower than that of air during photosynthesis and transpiration measurements (Fig. 5).

Table 1. Photosynthetic and transpiration rates, plant height, and root length density (RLD) in response to drip irrigation treatments: control or non-compensation (no water stress, fully irrigated), and two drip-irrigated partial root zone drying (PRD) treatments using vertically split-root system (PRD_{vert}) and two-compartment split-root system (PRD_{compt}).

Parameter	Treatment	Days after transplanting (DAT) on 13 June 2011*						
		37 (19 July)	51 (2 Aug.)	65 (16 Aug.)	79 (30 Aug.)	94 (14 Sep.)	114 (4 Oct.)	131 (21 Oct.)
Photosynthesis (μmol m^{-2} s^{-1})	Control	13.31a	15.70a	16.12a	10.13a	14.17a	8.98a	8.04a
	PRD_{vert}	13.33a	16.20a	16.11a	10.12a	14.00a	9.12a	8.06a

	PRD_{compt}	13.13a	16.16a	16.08a	10.11a	13.81a	10.03a	8.03a
Transpiration rate (mmol m^{-2} s^{-1})	Control	5.05ab	7.76a	6.18a	4.05a	4.81a	4.15a	3.22a
	PRD_{vert}	4.76b	7.73a	6.25a	4.00a	4.95a	4.13a	3.32a
	PRD_{compt}	5.474a	7.80a	6.13a	4.09a	4.90a	4.12a	3.20a
Plant height (cm)	Control	32.00a	46.03a	56.80a	59.14a	60.78a	66.05a	63.88a
	PRD_{vert}	30.05a	40.88a	51.23a	54.93a	57.53a	59.65b	62.90a
	PRD_{compt}	31.93a	47.78a	57.84a	60.86a	62.60a	65.65a	65.68a
RLD (cm root cm^{-3} soil)**	Control	0.071	-	0.083	-	0.085	-	0.071a
	PRD_{vert}	0.077	-	0.086	-	0.087	-	0.070a
	PRD_{compt}	0.068	-	0.085	-	0.088	-	0.072a

*Different letters within columns indicate significant differences by Tukey's Studentized range test at $P < 0.05$.
**On 37, 65, and 94DAT, one pot per treatment was sampled for RLD analysis, while on 131DAT, four pots per treatment were sampled.

No significant differences were noted in the root length distribution between PRD treatments and control (Table 1). Average plant height in all the treatments varied from 30 to 66 cm during the period from 2DAT to 142DAT. The difference in plant height between control, PRD_{vert} and PRD_{compt} treatments was not statistically significant (Table 1). Therefore, either of the two drip-irrigated PRD treatments has the potential to be adopted as water saving practices in chile production where limited water is available such as southern New Mexico.

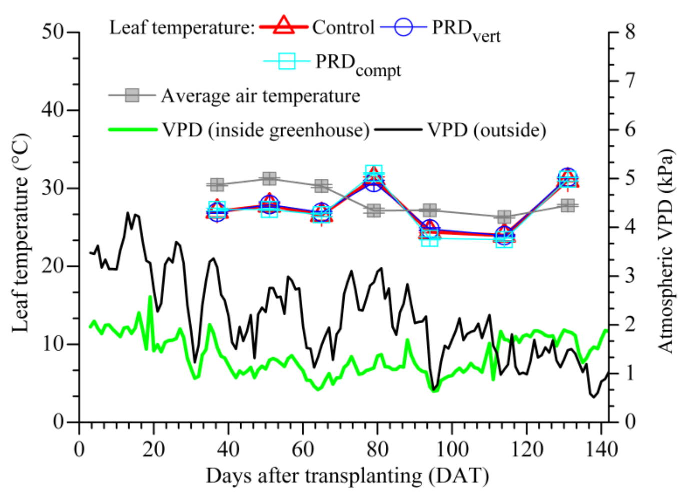

Fig. 5. Average air temperature, and leaf temperatures for control and two partial root zone drying (PRD) treatments using vertically split-root (PRD_{vert}) and two-compartment split-root (PRD_{compt}) systems during the time of photosynthesis and transpiration measurements (Table 1). Estimated daily atmospheric vapor pressure deficit (VPD) values inside and outside the greenhouse are shown during the period from 2DAT to 142 DAT (14 June to 31October, 2011).

Conclusions

Data obtained in this study suggest that both drip-irrigated PRD techniques have the potential to be adopted as water saving practices in chile production. Chile plants under PRD_{vert} and PRD_{compt} could compensate for water stress in one part of the vertical or lateral root zone profile by taking up water from less-stressed parts of the vertical or lateral root zone regions, without affecting root water uptake or transpiration or photosynthetic rates to meet peak water demand. No significant differences were noted in the root length distributions and plant heights between PRD treatments and the control. Although we evaluated PRD_{vert} and PRD_{compt} on greenhouse drip-irrigated chile plants grown in a soil-mix media and without the interference of rain, the application of these drip-irrigated PRD techniques to field-grown plants is expected to maintain similar advantages because chile is a deep rooted crop and therefore, roots will have a higher volume of soil to compensate for water stress. Further numerical assessment of compensatory root water uptake rates and their spatial distribution under PRD_{vert} and PRD_{compt} is recommended to extend the experimental findings.

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Irrigation Criteria for Sweet Potato Production Using Drip Irrigation

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Abstract. *An irrigation criterion has not been established for sweet potato (*Ipomoea batatas*) production in the Pacific Northwest. Four sweet potato varieties were planted at Ontario, Oregon, on silt loam. Slips were established for 30 days at 25 kPa and then subjected to four soil water tension (SWT) irrigation criteria (40, 60, 80, and 100 kPa) using drip irrigation. Vine growth, soil cover, water application, and sweet potato yield and grade were evaluated. Marketable (44.1 tons/acre) and US number 1 yield were greatest with a SWT irrigation criterion of 40 kPa, using 358 mm of water and the SWT averaged 28 kPa.*

Keywords. Ipomoea batatas, soil water tension, yield,

Introduction

Sweet potato is a versatile crop cultivated mainly for tuber production. It is a long-season crop grown mainly in the southeastern United States and in California. Research suggests that the availability of irrigation water together with high temperatures during summer favors production of high-quality sweet potatoes in eastern Oregon. Recently, growers have indicated interest in growing sweet potato as a new crop in eastern Oregon. The valley has a number of crop produce processors who are willing to buy sweet potatoes grown locally as a strategy to cut the costs associated with sweet potato trucking from California and the southeastern United States. Purchasing locally produced sweet potatoes could significantly reduce the carbon footprint of sweet potato processors in the Treasure Valley. Also, growers would be able to develop niche marketing for a crop that is loved by most consumers. Newly developed sweet potato varieties will produce mature tubers in 80 to 90 days, suggesting that plants transplanted in early June will produce mature tubers that could be harvested during September or early October, around the time of the first vegetation killing frost.

Critical factors for successful sweet potato production include irrigation scheduling and the amount of water to be applied. Irrigation scheduling options rely on the measurement of soil water content or soil water tension. Precise irrigation scheduling by soil water tension criteria is a powerful method to optimize plant performance. By utilizing the ideal soil water tension and adjusting irrigation duration and amount, it is possible to simultaneously achieve high productivity and meet environmental stewardship goals for water use and reduced leaching (Shock and Wang 2011).

Objectives

The overarching goal of this study was to assess the possibility of producing sweet potatoes in eastern Oregon. The specific objectives were to evaluate varieties and develop the irrigation criterion suitable for sweet potato production in eastern Oregon.

Materials and Methods

The field was plowed and disked during fall 2010 and fumigated on February 16, 2011 using metam sodium at 30 gal/acre through sprinklers. The beds (36 inches wide) were formed 3 weeks after fumigation followed by fertilizer to supply 100 lb nitrogen/acre that was shanked into beds. The study followed a split-plot design with irrigation criteria forming the main plots and varieties as subplots with treatments arranged in a randomized complete block. The study had three replications and drip tape was used to deliver irrigation water. Each subplot was 3 beds (9 ft wide) by 30 ft long.

Sweet potato slips were transplanted by hand on June 3 on 30 cm (12-inch) spacing within the row using the drip tape emitter spacing on top of the bed as markers. The drip tape used was Toro Aqua-traxx® 8-mil emitting 8,327 mm/min/30.5 m (0.22 gal/min/100 ft). Slips were transplanted 10 to 15 cm (4 to 6 inch) deep using a hand trowel. Plants were immediately irrigated for 5 hours (0.35 inch) in order to provide soil/transplant contact. Plots were irrigated again on June 4 for 2 hours (0.14 inch). Plants were irrigated again on June 10, 21 and July 5 to provide 0.5 inch of water each. Subsequent irrigations were automatically determined by the datalogger controller, depending on targeted criterion of soil water tension.

The irrigation criteria were 40, 60, 80, and 100 kPa of moisture tension and water was delivered through drip tape. Sweet potato plants in each plot were irrigated automatically and independently when the soil water tension dropped below the targeted irrigation criterion. The irrigation duration was predetermined based on the drip tape capacity to deliver 1.25 cm (0.5 inch) of water in 7 hours and 5 min per incident.

Soil water tension was measured in each main plot with four granular matrix sensors (GMS, Watermark Soil Moisture Sensors Model 200SS, Irrometer Co., Riverside, CA) installed at 20-cm (8-inch) depth in the center of 'Beauregard' rows. Sensors had been calibrated to local soil water tension (Shock et al. 1998). The sensors were connected to a datalogger (CR10X, Campbell Scientific, Logan, UT) through a multiplexer (AM 410 multiplexer, Campbell Scientific, Logan, UT). The datalogger read the sensors and recorded the hourly soil water tension.

The datalogger was programmed to check the sensor readings in each main plot every 12 hours and irrigate the appropriate main plot if the average soil water tension was below the targeted criterion. The irrigations were controlled by the datalogger using a controller (SDM CD16AC controller, Campbell Scientific, Logan, UT) connected to solenoid valves in each main plot. The irrigation water was supplied by a well that maintained a continuous and constant water pressure of 241 kPa (35 psi). The pressure in the drip lines was maintained at 69 kPa (10 psi) by pressure regulators in each main plot. The automated irrigation system was started on July 8 and was turned off on September 29, 2011.

Integrated Pest Management

Preplant herbicides were not used because of the field proximity to sensitive crops. All plots were sprayed with glyphosate 0.86 kg ae/ha (Roundup® at 22 fl oz/acre) on May 26, 2011 to control all emerged weeds prior to transplanting. Sethoxydim (Poast®) at 0.214 kg ai/acre (16 fl oz/acre) plus nonionic surfactant (0.25% v/v) was applied on June 27, 2011 to control grassy weeds. Plots were hand-weeded on June 27 and July 28, 2011 to remove all broadleaf weeds. Later weed cohorts were sparsely distributed and were periodically removed by hand.

Sweet potato vines were flailed on October 4 and roots were dug using a 2-row digger set at 45-cm (18-inch) depth. Roots were picked by hand from the center row and later graded following California standards (May and Scheuerman 1998). In summary, the roots were graded based on California standards: U.S. No.1 were of uniform size, 4.4 to 9 cm (1.75 to 3.5 inches) in diameter and 7.5 to 23 cm (3 to 9 inches) long; U.S. No. 2 (mediums) included misshapen tubers and with a minimum diameter of 4 cm (1.5 inches); Jumbo weighed more than 567 g (20 oz) and was true to type.

The data were subjected to analysis of variance using PROCGLM procedure in Statistical Analysis Software (SAS) and means were compared using Fisher's protected least significant difference procedure at $P \leq 0.05$.

Results and Discussion

The average soil water tension increased with the increase in the targeted irrigation criterion (Table 1). The total amount of water applied from transplanting to harvest includes the water used during the plant establishment phase (June 3 to July 8) and daily rainfall. Total amount of water decreased with the increase in the targeted soil water tension. Sweet potato irrigated at the 40 kPa criterion received a seasonal total of

357.8 mm (14.1 inches) of water compared to 146.1 mm (5.8 inches) at 100 kPa. The water use efficiency (ton/acre marketable yield per inch of water applied) reflected the total amount of water used, which was directly related to the irrigation frequency needed to maintain the targeted irrigation criterion (Fig. 1).

Percent vegetative ground cover at 49 days after transplanting (July 22) was not influenced by the different irrigation criteria (Table 2). Differences in average percent ground cover were related to varietal characteristics. Ground cover for 'Covington' and 'Diane' averaged 80 and 83 percent, respectively, compared to 94 percent for Beauregard and 'Evangeline'. These results are supported by the average runner length for different varieties on July 22 (Table 2). Covington and Diane had shorter runners (51 and 39 cm; 20 and 15 inches) compared to Beauregard and Evangeline, which averaged 89 cm (35 inches).

The number of sweet potato runners per hill at 117 days after transplanting (September 28) was similar among irrigation criteria (Table 3); however, there were differences in the number of runners per hill that were attributed to varieties. Covington and Beauregard averaged 8 and 9 runners, compared to 11 and 12 for Evangeline and Diane, respectively. Beauregard had the longest average runner length at 379 cm (149 inches) and Diane had the shortest at 165 cm (65 inches).

Sweet potato yield varied among irrigation criteria and varieties (Table 4). The highest marketable yields were obtained when plants were irrigated at 40 kPa of moisture tension. There was a gradual decline in root yield with the increase in the targeted soil water tension to trigger irrigation. All varieties produced much lower yield at 80 and 100 kPa. Previous studies by May and Scheuerman (1998) indicated improved yield when sweet potatoes were irrigated at 25 kPa throughout the season or 25 kPa during plant development and 100 kPa during the root bulking stage. It is important to note that the irrigation criterion will be influenced by the soil type. Because the varieties responded similarly to irrigation at 80 and 100 kPa, the irrigation criteria could be changed to 25, 40, 60, and 80 kPa in future studies.

Conclusion

The results indicated that sweet potatoes could be grown successfully in eastern Oregon. Varietal differences in terms of growth habits and yield in response to available moisture were noted. Subsequent studies could help to determine the best variety and irrigation criterion and confirm the preliminary results. We believe the positional placement of irrigation water with drip irrigation may have reduced the weed pressure that would be expected with furrow or overhead irrigation.

References

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Table 1. Average hourly soil water tension, total water applied, marketable yield, and water use efficiency (ton/ha marketable yield per mm of water applied) for sweet potato exposed to four irrigation treatments, Malheur Experiment Station, Oregon State University, Ontario, OR, 2011.

Soil water tension	Hourly soil water tension	Total water applied[1]	Marketable yield[2]	Water use efficiency
kPa	kPa	mm	ton/ha	ton/mm
40	27.7	357.8	44.1	0.12
60	44.4	256.2	38.2	0.15
80	48.6	158.8	24.8	0.16
100	58.9	146.1	23.6	0.16
LSD (0.05)	4.2	40.3	3.1	0.02

[1] Total applied water for each criterion includes the amount applied uniformly to all treatments during plant establishment phase (37.8 mm) and rainfall from June 3 to September 29, 2011 (27.9 mm). 25.4 mm = 1 in.
[2]1 metric ton/ha is equivalent to 892 lb/acre.

Table 2. Sweet potato vegetative percent ground cover and average runner length on July 22 (49 days after transplanting) in response to differential irrigation criteria at Malheur Experiment Station, Ontario, OR, 2011.

Irrigation criterion	Percent ground cover				Average runner length			
	Covington	Beauregard	Evangeline	Diane	Covington	Beauregard	Evangeline	Diane
(kPa)	------------------------ % ----------------------				--------------------------- cm --------------------------			
40	88	95	94	83	56	107	91	43
60	75	93	94	83	48	84	79	33
80	82	93	93	83	51	81	86	38
100	75	94	93	80	48	89	86	41
LSD (0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Average[1]	80 b	94 a	94 a	83 b	51 b	91 a	86 a	39 b

[1] Because there was no significant difference among irrigation criteria, the means among water tension were used to compare variety performance. Average values within a row and group followed by the same letter are not significantly different according to LSD 0.05%.

Table 3. Number of sweet potato runners per hill and average length (cm) on September 28 (117 days after transplanting) in response to differential irrigation criteria at Malheur Experiment Station, Ontario, OR, 2011.

Irrigation criterion	Number of runners/hill				Average length/runner			
	Covington	Beauregard	Evangeline	Diane	Covington	Beauregard	Evangeline	Diane
(kPa)	------------------------ Number -----------------------				--------------------------- cm --------------------------			
40	6	9	9	11	224	452	358	198
60	6	9	10	12	213	399	340	175
80	13	10	12	12	145	348	262	158
100	5	8	11	12	175	315	226	130
LSD (0.05)	NS	NS	NS	NS	36	36	36	91
Average[1]	8 b	9 b	11 a	12 a	191 c	379 a	297 b	165 c

[1] Because there was no significant difference among irrigation criteria, the means among water tension were used to compare variety performance. Average values within a row and group followed by the same letter are not significantly different according to LSD 0.05%.

Table 4. Sweet potato yield and grade in response to differential irrigation criteria and variety at Malheur Experiment Station, Oregon State University, Ontario, OR, 2011.

Irrigation criterion	Sweet potato yield[1]					
	Total	Marketable	U.S. No. 2	U.S. No. 1	Jumbo	Discard[2]
(kPa)	(tons/ha)[3]					
	Beauregard					
40	54.2	49.4	9.7	34.6	5.1	4.8
60	51.6	47.1	8.7	32.8	5.6	4.5
80	38.2	32.2	6.5	22.4	3.4	6.0
100	33.2	27.8	6.6	20.8	0.4	5.4
Average	44.3	39.1	7.9	27.6	3.6	5.2
	Covington					
40	53.6	41.4	15.9	24.5	1.0	12.2
60	42.2	31.1	13.0	17.7	0.4	11.1
80	31.8	16.8	9.5	7.3	0.0	15.1
100	30.4	15.0	6.4	8.6	0.0	15.4
Average	39.5	26.1	11.2	14.5	0.4	13.4
	Diane					
40	49.5	43.0	5.5	35.1	2.4	6.5
60	42.3	38.3	5.5	31.0	1.8	4.0
80	34.2	29.1	6.4	21.3	1.3	5.2
100	32.8	29.0	4.8	21.2	3.0	3.8
Average	39.7	34.8	5.6	27.2	2.1	4.9
	Evangeline					
40	48.6	42.6	7.5	32.0	3.1	6.0
60	41.3	36.5	6.9	27.9	1.7	4.9
80	27.1	21.3	5.7	14.1	1.5	5.9
100	28.5	22.7	5.5	14.4	2.7	8.3
Average	36.4	30.8	6.4	22.1	2.3	5.6
LSD (0.05)						
Irrigation	2.7	3.1	1.3	3.1	1.2	1.3
Variety	2.7	3.1	1.4	3.1	1.3	1.4
Irrigat. X Variety	NS	NS	2.2	NS	NS	NS

[1] Sweet potato grades were based on California standards: U.S. No.1 were of uniform size, 4.4 to 9 cm (1.75 to 3.5 inches) in diameter and 7.5 to 23 cm (3 to 9 inches) long; U.S. No. 2 (mediums) included misshapen tubers and with a minimum diameter of 4 cm (1.5 inches); Jumbo weighed more than 567 g (20 oz) and were true to type.
[2] Discarded roots were <3.8 cm (<1.5 inches) in diameter.
[3]1 metric ton/ha is equivalent to 892 lb/acre.

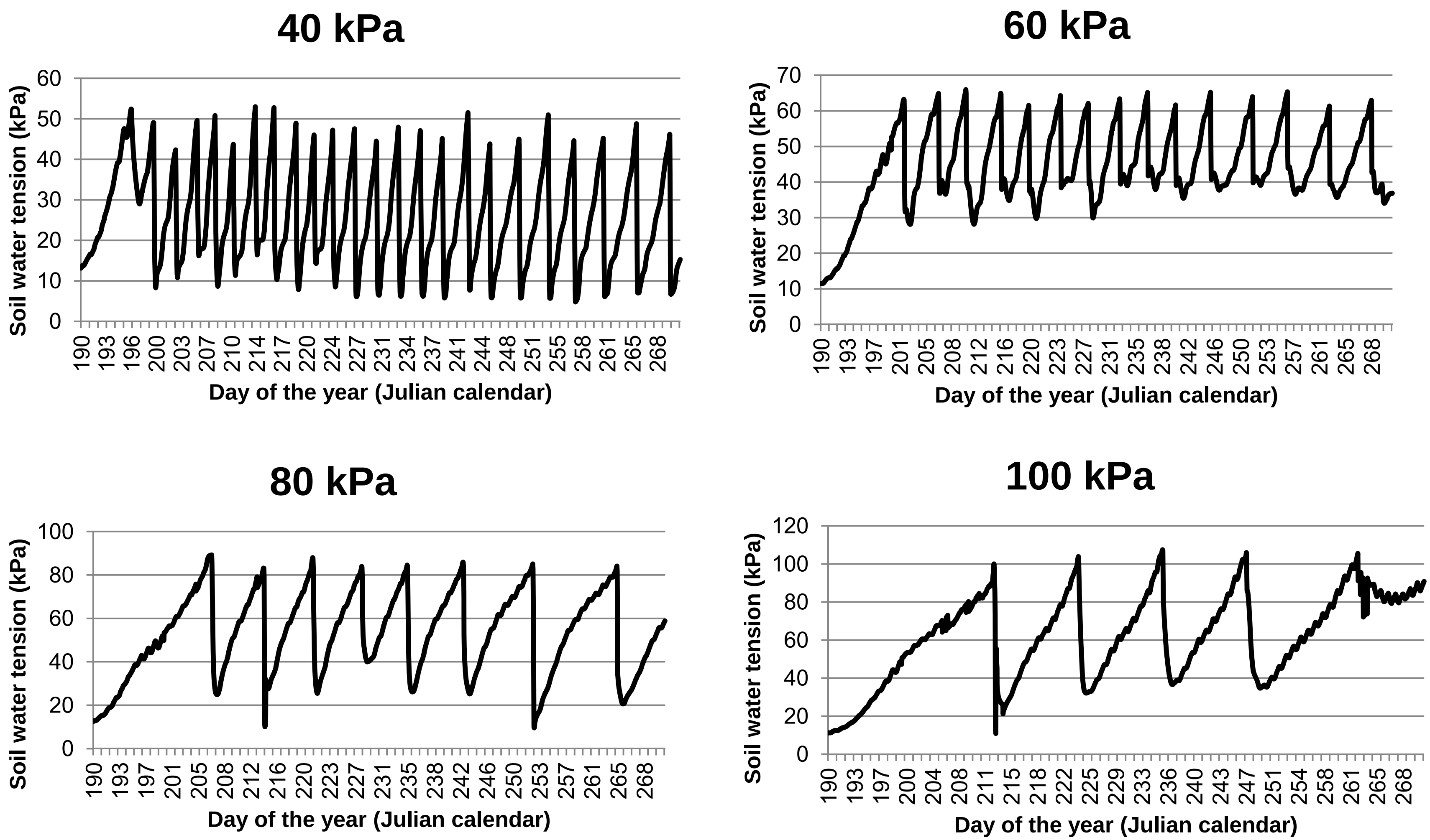

Figure 1. Soil water tension at 17.8-cm (7-inch) depth over time for sweet potato production at Malheur Experiment Station, Oregon State University, Ontario, OR, 2011. Each peak represents 1.25 cm (0.5 inch) of water delivered by drip irrigation with different irrigation criteria.

Long Term SDI for Seed Production of Western Rangeland Native Wildflower

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Abstract. *Native wildflower seed is needed to restore rangelands of the Intermountain West. Thirteen native forb species chosen by the US Forest Service and the Bureau of Reclamation were tested for their seed yield response to three low rates of subsurface drip irrigation (SDI) at Ontario, Oregon. Drip tape was installed 0.3 m deep and 1.52 m apart. Rows of seed were drilled 0.76 m apart aligned equidistant from a drip tape. Each plot of each specie consisted of four rows of plants with the middle two harvested for seed yield. The three irrigation treatments were a non-irrigated check, 25 mm per irrigation (100 mm/season), and 50 mm per irrigation (200 mm/season) replicated four times. Irrigation treatments consisted of four irrigations that were applied approximately every 2 weeks starting independently with the flowering of each forb species. The total irrigation requirements for these arid-land species were low and varied by species.*

Keywords. Subsurface drip irrigation, forb, irrigation management, zeric plants

Introduction

Native wildflower seed is needed to restore rangelands of the Intermountain West. Commercial seed production is necessary to provide the quantity of seed needed for restoration efforts. A major limitation to economically viable commercial production of native wildflower (forb) seed is stable and consistent seed productivity over years.

In natural rangelands, the natural variations in spring rainfall and soil moisture result in highly unpredictable water stress at flowering, seed set, and seed development, which for other seed crops is known to compromise seed yield and quality.

Native wildflower plants are not adapted to croplands. Native plants often are not competitive with crop weeds in cultivated fields. Poor competition with weeds could also limit wildflower seed production. Both sprinkler and furrow irrigation could provide supplemental water for seed production, but these irrigation systems risk further encouraging weeds. Also, sprinkler and furrow irrigation can lead to the loss of plant stand and seed production due to fungal pathogens. By burying drip tapes at 12-inch depth and avoiding wetting the soil surface, we hoped to assure flowering and seed set without undue encouragement of weeds or opportunistic diseases. The trials reported here tested the effects of three low rates of irrigation on the seed yield of 13 native forb species.

Materials and Methods

Plant Establishment

Seed of the seven Intermountain West forb species (the first seven species in Table 1) was received in late November in 2004 from the Rocky Mountain Research Station (Boise, ID). The plan was to plant the seed in the fall of 2004, but due to excessive rainfall in October, the ground preparation was not completed and planting was postponed to early 2005. To try to ensure germination, the seed was submitted to cold stratification. The seed was soaked overnight in distilled water on January 26, 2005, after which the water was drained and the seed soaked for 20 min in a 10 percent by volume solution of 13 percent bleach in distilled water. The water was drained and the seed was placed in thin layers in plastic containers. The plastic containers had lids with holes drilled in them to allow air movement. These containers were placed in a cooler set at approximately 34°F. Every few days the seed was mixed and, if necessary, distilled water added to maintain seed moisture. In late February, seed of *Lomatium grayi* and *L. triternatum* had started to sprout.

In late February, 2005 drip tape (T-Tape TSX 515-16-340) was buried at 12-inch depth between 2 30-inch rows of a Nyssa silt loam with a pH of 8.3 and 1.1 percent organic matter. The drip tape was buried in alternating inter-row spaces (5 ft apart). The flow rate for the drip tape was 0.34 gal/min/100 ft at 8 psi with emitters spaced 16 inches apart, resulting in a water application rate of 0.066 inch/hour.

On March 3, seed of all species was planted in 30-inch rows using a custom-made plot grain drill with disk openers. All seed was planted at 20-30 seeds/ft of row. The *Eriogonum umbellatum* and the *Penstemon* spp. were planted at 0.25-inch depth and the *Lomatium* spp. at 0.5-inch depth. The trial was irrigated with a minisprinkler system (R10 Turbo Rotator, Nelson Irrigation Corp., Walla Walla, WA) for even stand establishment from March 4 to April 29. Risers were spaced 25 ft apart along the flexible polyethylene hose laterals that were spaced 30 ft apart and the water application rate was 0.10 inch/hour. A total of 1.72 inches of water was applied with the minisprinkler system. *Eriogonum umbellatum*, *Lomatium triternatum*, and *L. grayi* started emerging on March 29. All other species except *L. dissectum* emerged by late April. Starting June 24, the field was irrigated with the drip system. A total of 3.73 inches of water was applied with the drip system from June 24 to July 7. The field was not irrigated further in 2005.

Plant stands for *Eriogonum umbellatum*, *Penstemon* spp., *Lomatium triternatum*, and *L. grayi* were uneven. *Lomatium dissectum* did not emerge. None of the species flowered in 2005. In early October, 2005 more seed was received from the Rocky Mountain

Research Station for replanting. The empty lengths of row were replanted by hand in the *E. umbellatum* and *Penstemon* spp. plots. The *Lomatium* spp. plots had the entire row lengths replanted using the planter. The seed was replanted on October 26, 2005. In the spring of 2006, the plant stands of the replanted species were excellent, except for *P. deustus*.

On April 11, 2006 seed of three globemallow species (*Sphaeralcea parvifolia, S. grossulariifolia, S. coccinea),* two prairie clover species *(Dalea searlsiae, D. ornata)*, and basalt milkvetch (*Astragalus filipes*) was planted at 30 seeds/ft of row. The field was sprinkler irrigated until emergence. Emergence was poor. In late August of 2006 seed of the three globemallow species was harvested by hand. On November 9, 2006 the six forbs that were planted in 2006 were mechanically flailed and on November 10, they were replanted. On November 11, the *Penstemon deustus* plots were also replanted at 30 seeds/ft of row.

Table 1. Forb species planted in the drip irrigation trials at the Malheur Experiment Station, Oregon State University, Ontario, OR.

Species	Common names
Eriogonum umbellatum	Sulfur-flower buckwheat
Penstemon acuminatus	Sharpleaf penstemon, sand-dune penstemon
Penstemon deustus	Scabland penstemon, hotrock penstemon
Penstemon speciosus	Royal penstemon, sagebrush penstemon
Lomatium dissectum	Fernleaf biscuitroot
Lomatium triternatum	Nineleaf biscuitroot, nineleaf desert parsley
Lomatium grayi	Gray’s biscuitroot, Gray’s lomatium
Sphaeralcea parvifolia	Smallflower globemallow
Sphaeralcea grossulariifolia	Gooseberryleaf globemallow
Sphaeralcea coccinea	Scarlet globemallow, red globemallow
Dalea searlsiae	Searls’ prairie clover
Dalea ornata	Western prairie clover, Blue Mountain prairie clover
Astragalus filipes	Basalt milkvetch

Irrigation for Seed Production

In April, 2006 each planted strip of each forb species was divided into plots 30 ft long. Each plot contained four rows of each species. The experimental designs were randomized complete blocks with four replicates. The three irrigation treatments were a nonirrigated check, 1 inch per irrigation, and 2 inches per irrigation. Each treatment received 4 irrigations that were applied approximately every 2 weeks starting with flowering of the forbs. The amount of water applied to each treatment was calculated by the length of time necessary to deliver 1 or 2 inches through the drip system; the amount was measured by a water meter and recorded after each irrigation to ensure correct water applications. Irrigations were controlled with a controller and solenoid valves.

In March of 2007, the drip-irrigation system was modified to allow separate irrigation of the species due to different timings of flowering. The three *Lomatium* spp. were irrigated together and *Penstemon deustus* and *P. speciosus* were irrigated together, but separately from the others. *Penstemon acuminatus* and *Eriogonum umbellatum* were irrigated individually. In early April, 2007 the three globemallow species*,* two prairie clover species, and basalt milkvetch were divided into plots with a drip-irrigation system to allow the same irrigation treatments that were received by the other forbs.

Irrigation dates can be found in Table 2. In 2007, irrigation treatments were inadvertently continued after the fourth irrigation. In 2007, irrigation treatments for all species were continued until the last irrigation on June 24.

Soil volumetric water content was measured by neutron probe. The neutron probe was calibrated by taking soil samples and probe readings at 8-, 20-, and 32-inch depths during installation of the access tubes. The soil water content was determined volumetrically from the soil samples and regressed against the neutron probe readings, separately for each soil depth. Regression equations were then used to transform the neutron probe readings into volumetric soil water content.

Flowering, Harvesting, and Seed Cleaning

Flowering dates for each species were recorded (Table 2). The *Eriogonum umbellatum* and *Penstemon* spp. plots produced seed in 2006, in part because they had emerged in the spring of 2005. Each year, the middle two rows of each plot were harvested when seed of each species was mature (Table 2), using the methods listed in Table 3. The plant stand for *P. deustus* was too poor to result in reliable seed yield estimates. Replanting of *P. deustus* in the fall of 2006 did not result in adequate plant stand in the spring of 2007.

Eriogonum umbellatum seeds did not separate from the flowering structures in the combine; the unthreshed seed was taken to the U.S. Forest Service Lucky Peak Nursery (Boise, ID) and run through a dewinger to separate seed. The seed was further cleaned in a small clipper seed cleaner.

Penstemon deustus seed pods were too hard to be opened in the combine; the unthreshed seed was precleaned in a small clipper seed cleaner and then seed pods were broken manually by rubbing the pods on a ribbed rubber mat. The seed was then cleaned again in the small clipper seed cleaner.

Penstemon acuminatus and *P. speciosus* were threshed in the combine and the seed was further cleaned using a small clipper seed cleaner.

Cultural Practices in 2006

On October 27, 2006, 50 lb phosphorus (P)/acre and 2 lb zinc (Zn)/acre were injected through the drip tape to all plots of *Eriogonum umbellatum*, *Penstemon* spp., and *Lomatium* spp. On November 11, 100 lb nitrogen (N)/acre as urea was broadcast to all *Lomatium* spp. plots. On November 17, all plots of *Eriogonum umbellatum*, *Penstemon* spp. (except *P. deustus*), and *Lomatium* spp. had Prowl® at 1 lb ai/acre broadcast on the soil surface. Irrigations for all species were initiated on May 19 and terminated on June 30. Harvesting and seed cleaning methods for each species are listed in Table 3.

Cultural Practices in 2007

Penstemon acuminatus and *P. speciosus* were sprayed with Aza-Direct® at 0.0062 lb ai/acre on May 14 and 29 for lygus bug control. Irrigations for each species were initiated and terminated on different dates (Table 2). Harvesting and seed cleaning methods for each species are listed in Table 3. All plots of the *Sphaeralcea* spp. were flailed on November 8, 2007.

Cultural Practices in 2008

On November 9, 2007 and on April 15, 2008, Prowl at 1 lb ai/acre was broadcast on all plots for weed control. Capture® 2EC at 0.1 lb ai/acre was sprayed on all plots of *Penstemon acuminatus* and *P. speciosus* on May 20 for lygus bug control. Irrigations for each species were initiated and terminated on different dates (Table 2). Harvesting and seed cleaning methods for each species are listed in Table 3.

Cultural Practices in 2009

On March18, Prowl at 1 lb ai/acre and Volunteer® at 8 oz/acre were broadcast on all plots for weed control. On April 9, 50 lb N/acre and 10 lb P/acre were applied through the drip irrigation system to the three *Lomatium* species.

The flowering, irrigation timing, and harvest timing were recorded for each species (Table 2). Harvesting and seed cleaning methods for each species are listed in Table 3. On December 4, 2009, Prowl at 1 lb ai/acre was broadcast for weed control on all plots.

Cultural Practices in 2010

The flowering, irrigation, and harvest timing of the established forbs were recorded for each species (Table 2). Harvesting and seed cleaning methods for each species are listed in Table 3. On November 17, Prowl at 1 lb ai/acre was broadcast on all plots for weed control.

Cultural Practices in 2011

On May 3, 2011, 50 lb N/acre was applied to all *Lomatium* spp. plots as uran injected through the drip tape. The flowering, irrigation, and harvest timing varied by species (Table 2). Harvesting and seed cleaning methods for each species are listed in Table 3.

Table 2. Native forb flowering, irrigation, and seed harvest dates by species in 2006–2011, Malheur Experiment Station, Oregon State University, Ontario, OR.

	Flowering			Irrigation		
Species	Start	Peak	End	Start	End	Harvest
				2006		
Eriogonum umbellatum	19-May		20-Jul	19-May	30-Jun	3-Aug
Penstemon acuminatus	2-May	10-May	19-May	19-May	30-Jun	7-Jul
Penstemon deustus	10-May	19-May	30-May	19-May	30-Jun	4-Aug
Penstemon speciosus	10-May	19-May	30-May	19-May	30-Jun	13-Jul
Lomatium dissectum				19-May	30-Jun	
Lomatium triternatum				19-May	30-Jun	
Lomatium grayi				19-May	30-Jun	
Sphaeralcea parvifolia						
S. grossulariifolia						
Sphaeralcea coccinea						
Dalea searlsiae						
Dalea ornata						
				2007		
Eriogonum umbellatum	25-May		25-Jul	2-May	24-Jun	31-Jul
Penstemon acuminatus	19-Apr		25-May	19-Apr	24-Jun	9-Jul
Penstemon deustus	5-May	25-May	25-Jun	19-Apr	24-Jun	
Penstemon speciosus	5-May	25-May	25-Jun	19-Apr	24-Jun	23-Jul
Lomatium dissectum				5-Apr	24-Jun	
Lomatium triternatum	25-Apr		1-Jun	5-Apr	24-Jun	29-Jun, 16-Jul
Lomatium grayi	5-Apr		10-May	5-Apr	24-Jun	30-May, 29-Jun
Sphaeralcea parvifolia	5-May	25-May		16-May	24-Jun	20-Jun, 10-Jul, 13-Aug
S. grossulariifolia	5-May	25-May		16-May	24-Jun	20-Jun, 10-Jul, 13-Aug
Sphaeralcea coccinea	5-May	25-May		16-May	24-Jun	20-Jun, 10-Jul, 13-Aug
Dalea searlsiae						20-Jun, 10-Jul
Dalea ornata						20-Jun, 10-Jul
				2008		
Eriogonum umbellatum	5-Jun	19-Jun	20-Jul	15-May	24-Jun	24-Jul
Penstemon acuminatus	29-Apr		5-Jun	29-Apr	11-Jun	11-Jul
Penstemon deustus	5-May		20-Jun	29-Apr	11-Jun	
Penstemon speciosus	5-May		20-Jun	29-Apr	11-Jun	17-Jul
Lomatium dissectum				10-Apr	29-May	
Lomatium triternatum	25-Apr		5-Jun	10-Apr	29-May	3-Jul
Lomatium grayi	25-Mar		15-May	10-Apr	29-May	30-May, 19-Jun
Sphaeralcea parvifolia	5-May		15-Jun	15-May	24-Jun	21-Jul
S. grossulariifolia	5-May		15-Jun	15-May	24-Jun	21-Jul
Sphaeralcea coccinea	5-May		15-Jun	15-May	24-Jun	21-Jul
Dalea searlsiae		19-Jun				
Dalea ornata		19-Jun				

Table 2, continued. Native forb flowering, irrigation, and seed harvest dates by species in 2006–2011. Malheur Experiment Station, Oregon State University, Ontario, OR.

	Flowering			Irrigation		
Species	Start	Peak	End	Start	End	Harvest
			2009			
Eriogonum umbellatum	31-May		15-Jul	19-May	24-Jun	28-Jul
Penstemon acuminatus	2-May		10-Jun	8-May	12-Jun	10-Jul
Penstemon deustus				19-May	24-Jun	
Penstemon speciosus	14-May		20-Jun	19-May	24-Jun	10-Jul
Lomatium dissectum	10-Apr		7-May	20-Apr	28-May	16-Jun
Lomatium triternatum	10-Apr	7-May	1-Jun	20-Apr	28-May	26-Jun
Lomatium grayi	10-Mar		7-May	20-Apr	28-May	16-Jun
Sphaeralcea parvifolia	1-May		10-Jun	22-May	24-Jun	14-Jul
Sphaeralcea grossulariifolia	1-May		10-Jun	22-May	24-Jun	14-Jul
Sphaeralcea coccinea	1-May		10-Jun	22-May	24-Jun	14-Jul
			2010			
Eriogonum umbellatum	4-Jun	12-19 Jun	15-Jul	28-May	8-Jul	27-Jul
Penstemon speciosus	14-May		20-Jun	12-May	22-Jun	22-Jul
Lomatium dissectum	25-Apr		20-May	15-Apr	28-May	21-Jun
Lomatium triternatum	25-Apr		15-Jun	15-Apr	28-May	22-Jul
Lomatium grayi	15-Mar		15-May	15-Apr	28-May	22-Jun
Sphaeralcea parvifolia	10-May	4-Jun	25-Jun	28-May	8-Jul	20-Jul
Sphaeralcea grossulariifolia	10-May	4-Jun	25-Jun	28-May	8-Jul	20-Jul
Sphaeralcea coccinea	10-May	4-Jun	25-Jun	28-May	8-Jul	20-Jul
			2011			
Eriogonum umbellatum	8-Jun	30-Jun	20-Jul	20-May	5-Jul	1-Aug
Penstemon speciosus	25-May	30-May	30-Jun	20-May	5-Jul	29-Jul
Lomatium dissectum	8-Apr	25-Apr	10-May	21-Apr	7-Jun	20-Jun
Lomatium triternatum	30-Apr	23-May	15-Jun	21-Apr	7-Jun	26-Jul
Lomatium grayi	1-Apr	25-Apr	13-May	21-Apr	7-Jun	22-Jun
Sphaeralcea parvifolia	26-May	15-Jun	14-Jul	20-May	5-Jul	29-Jul
Sphaeralcea grossulariifolia	26-May	15-Jun	14-Jul	20-May	5-Jul	29-Jul
Sphaeralcea coccinea	26-May	15-Jun	14-Jul	20-May	5-Jul	29-Jul

Table 3. Native forb seed harvest and cleaning by species, Malheur Experiment Station, Oregon State University, Ontario, OR.

Species	Number of harvests/year	Harvest method	Pre-cleaning	Threshing method	Cleaning method
Eriogonum umbellatum	1	combine[a]	none	dewinger[b]	mechanical[c]
Penstemon acuminatus	1	combine[d]	none	combine	mechanical[c]
Penstemon deustus	1	combine[a]	mechanical[c]	hand[e]	mechanical[c]
Penstemon speciosus[f]	1	combine[d]	none	combine	mechanical[c]
Lomatium dissectum	1	hand	hand	none	mechanical[c]
Lomatium triternatum	1 – 2	hand	hand	none	mechanical[c]
Lomatium grayi	1 – 2	hand	hand	none	mechanical[c]
Sphaeralcea parvifolia	1 – 3	hand or combine[d]	none	combine	none
Sphaeralcea grossulariifolia	1 – 3	hand or combine[d]	none	combine	none
Sphaeralcea coccinea	1 – 3	hand or combine[d]	none	combine	none
Dalea searlsiae	0 or 2	hand	none	dewinger	mechanical[c]
Dalea ornate	0 or 2	hand	none	dewinger	mechanical[c]

[a] Wintersteiger Nurserymaster small-plot combine with dry bean concave.
[b] Specialized seed threshing machine at USDA Lucky Peak Nursery used in 2006. Thereafter an adjustable hand-driven corn grinder was used to thresh seed.
[c] Clipper seed cleaner.
[d] Wintersteiger Nurserymaster small-plot combine with alfalfa seed concave. For the *Sphaeralcea* spp., flailing in the fall of 2007 resulted in more compact growth and one combine harvest in 2008, 2009, and 2010.
[e] Hard seed pods were broken by rubbing against a ribbed rubber mat.
[f] Harvested by hand in 2007 and 2009 due to poor seed set.

Results and Discussion

The soil volumetric water content in the various species in 2011 responded to the irrigation treatments on each species and remained fairly moist due to winter snow pack, heavy spring rainfall, and the late distribution of precipitation.

Flowering and Seed Set

Penstemon acuminatus and *P. speciosus* had poor seed set in 2007, partly due to a heavy lygus bug infestation that was not adequately controlled by the applied insecticides. In the Treasure Valley, the first hatch of lygus bugs occurs when 250 degree-days (52°F base) are accumulated. Data collected by an AgriMet weather station adjacent to the field indicated that the first lygus bug hatch occurred on May 14, 2006; May 1, 2007; May 18, 2008; May 19, 2009; and May 29, 2010. The average (1995-2010) lygus bug hatch date was May 18. *Penstemon acuminatus* and *P. speciosus* start flowering in early May. The earlier lygus bug hatch in 2007 probably resulted in harmful levels of lygus bugs present during a larger part of the *Penstemon* spp. flowering period than normal. Poor seed set for *P. acuminatus* and *P. speciosus* in 2007 also was related to poor vegetative growth compared to 2006 and 2008. In 2009, all plots of *P. acuminatus* and *P. speciosus* again showed poor vegetative growth and seed set. Root rot affected all plots of *P. acuminatus* in 2009, killing all plants in two of the four plots of the wettest treatment (2 inches per irrigation). Root rot affected the wetter plots of *P. speciosus* in 2009, but the stand partially recovered due to natural reseeding.

The three *Sphaeralcea* spp. (globemallow) showed a long flowering period (early May through September) in 2007. Multiple manual harvests were necessary because the seed falls out of the capsules once they are mature. The flailing of the three *Sphaeralcea* spp. starting in the fall of 2007 was done annually to induce a more concentrated flowering, allowing only one mechanical harvest. Precipitation in June of 2009 (2.27 inches) and 2010 (1.95 inches) was substantially higher than average (0.76 inches). Rust (*Puccinia sherardiana*) infected all three *Sphaeralcea* spp. in June of 2009 and 2010, causing substantial leaf loss and reduced vegetative growth.

Seed Yields

Eriogonum umbellatum

In 2006, seed yield of *Eriogonum umbellatum* increased with increasing water application, up to 8 inches, the highest amount tested (Table 5). In 2007-2009 seed yield showed a quadratic response to irrigation rate (Tables 5 and 6). Seed yields were maximized by 8.1 inches, 7.2 inches, and 6.9 inches of water applied in 2007, 2008, and 2009, respectively. In 2010, there was no significant difference in yield between treatments. In 2011, seed yield was highest with no irrigation. The 2010 and 2011 seasons had unusually cool (Table 4) and wet weather. The accumulated precipitation in April through June of 2010 and 2011 was the highest over the years of the trial (Table 4). The relatively high seed yield of *E. umbellatum* in the nonirrigated treatment in 2010 and 2011 seemed to be related to the high spring precipitation. The negative effect of irrigation on seed yield in 2011 might have been related to the presence of rust. Irrigation could have exacerbated the rust and resulted in lower yields. Averaged over 6 years, seed yield of *E. umbellatum* increased with increasing water applied up to 8 inches, the highest amount tested. The quadratic seed yield responses most years suggests that additional irrigation above 8 inches would not be beneficial.

Penstemon acuminatus

There was no significant difference in seed yield between irrigation treatments for *P. acuminatus* in 2006 (Table 5). Precipitation from March through June was 6.4 inches in 2006. The 64-year-average precipitation from March through June is 3.6 inches. The wet weather in 2006 could have attenuated the effects of the irrigation treatments. In 2007, seed yield showed a quadratic response to irrigation rate. Seed yields were maximized by 4.0 inches of water applied in 2007. In 2008, seed yield showed a linear response to applied water. In 2009, there was no significant difference in seed yield between treatments (Table 6). However, due to root rot affecting all plots in 2009, the seed yield results were compromised. By 2010, substantial lengths of row contained only dead plants. Measurements in each plot showed that plant death increased with increasing irrigation rate. The stand loss was 51.3, 63.9, and 88.5 percent for the 0-, 4-, and 8-inch irrigation treatments, respectively. The trial area was disked out in 2010. Following the 2005 planting, seed yields were substantial in 2006 and moderate in 2008. *P. acuminatus* is a short-lived perennial.

Penstemon speciosus

In 2006-2009 seed yield of *P. speciosus* showed a quadratic response to irrigation rate (Tables 5 and 6). Seed yields were maximized by 4.3, 4.2, 5.0, and 4.3 inches of water applied in 2006, 2007, 2008, and 2009, respectively. In 2010 and 2011, there was no difference in seed yield between treatments. Seed yield was low in 2007 due to lygus bug damage, as discussed previously. Seed yield in 2009 was low due to stand loss from root rot. The plant stand recovered somewhat in 2010 and 2011, due in part to natural reseeding, especially in the nonirrigated plots.

Penstemon deustus

There was no significant difference in seed yield between irrigation treatments for *P. deustus* in 2006 or 2007. Both the replanting of the low stand areas in October 2005 and the replanting of the whole area in October 2006 resulted in very poor emergence and plots with very low and uneven stands. The planting was disked out.

Lomatium triternatum

Lomatium triternatum showed a trend for increasing seed yield with increasing irrigation rate in 2007 (Table 5). The highest irrigation rate resulted in significantly higher seed yield than the nonirrigated check treatments. Seed yields of *L. triternatum* were substantially higher in 2008-2011 (Tables 5 and 6). In 2008–2011 seed yields of *L. triternatum* showed a quadratic response to irrigation rate. Seed yields were estimated to be maximized by 8.4, 5.4, 7.8, and 4.1 inches of water applied in 2008, 2009, 2010, and 2011, respectively. Averaged over 5 years, seed yield of *L. triternatum* was estimated to be maximized by 5.1 inches of applied water. Irrigation requirements were lower in 2011.

Lomatium grayi

Lomatium grayi showed a trend for increasing seed yield with increasing irrigation rate in 2007 (Table 5). The highest irrigation rate resulted in significantly higher seed yield than the nonirrigated check. Seed yields of *L. grayi* were substantially higher in 2008 and 2009. In 2008, seed yields of *L. grayi* showed a quadratic response to irrigation rate. Seed yields were estimated to be maximized by 6.9 inches of water applied in 2008. In 2009, seed yield showed a linear response to irrigation rate. Seed yield with the 4-inch irrigation rate was significantly higher than in the nonirrigated check, but the 8-inch irrigation rate did not result in a significant increase above the 4-inch rate. In 2010, seed yield was not responsive to irrigation. The unusually wet spring of 2010 could have caused the lack of response to irrigation. A further complicating factor in 2010 that compromised seed yields was rodent damage. Extensive rodent (vole) damage occurred over the 2009-2010 winter. The affected areas were transplanted with 3-year-old *L. grayi* plants from an adjacent area in the spring of 2010. To reduce their attractiveness to voles, the plants were mowed after becoming dormant in early fall of 2010. In 2011, seed yield again did not respond to irrigation. The spring of 2011 was unusually cool and wet. Averaged over 5 years, seed yield of *L. grayi* was estimated to be maximized by 5.1 inches of applied water. More appropriately, irrigation probably should be variable according to precipitation.

Lomatium dissectum

Lomatium dissectum had very poor vegetative growth in 2006-2008, and produced only very small amounts of flowers in 2008. In 2009, vegetative growth and flowering for *L. dissectum* were greater. Seed yield of *L. dissectum* showed a linear response to irrigation rate in 2009. Seed yield with the 4-inch irrigation rate was significantly higher than with the nonirrigated check, but the 8-inch irrigation rate did not result in a significant increase above the 4-inch rate. In 2010 and 2011, seed yields of *L. dissectum* showed a quadratic response to irrigation rate. Seed yields were estimated to be maximized by 5.4 and 5.1 inches of applied water in 2010 and 2011, respectively. Averaged over the 3 years, seed yield showed a quadratic response to irrigation rate and was estimated to be maximized by 5.6 inches of applied water.

All the *Lomatium* species tested were affected by *Alternaria* fungus, but the infection was greatest on the *L. dissectum* selection planted in this trial. This infection might have delayed *L. dissectum* plant development.

Sphaeralcea spp.

In 2007-2011 there were no significant differences in seed yield among irrigation treatments for the three *Sphaeralcea* species (Tables 5 and 6).

Dalea ornata and *D. searlsiae*

Emergence for the two *Dalea* spp. was poor, and plots had poor and uneven stands. In 2007, there was no significant difference in seed yield among irrigation treatments for the two *Dalea* spp., but *D. ornata* had the higher seed yield. The stand of the two species declined and was too poor for seed harvest in 2008. They were replanted in the fall of 2008, but emergence was again poor and stands were not adequate for seed harvest in 2009 and the planting was destroyed.

Conclusions

Subsurface drip irrigation systems were tested for native seed production because they have two potential strategic advantages: a) low water use, and b) the buried drip tape provides water to the plants at depth, precluding stimulation of weed seed germination on the soil surface and keeping water away from native plant tissues that are not adapted to a wet environment.

Due to the arid environment, supplemental irrigation may often be required for successful flowering and seed set because soil water reserves may be exhausted before seed formation. The total irrigation requirements for these arid-land species were low and varied by species (Table 7). The *Sphaeralcea* spp. and *Penstemon acuminatus* did not respond to irrigation in these trials. Natural rainfall was sufficient to maximize seed production in the absence of weed competition.

Lomatium dissectum required approximately 6 inches of irrigation. *Lomatium grayi, L. triternatum*, and *Eriogonum umbellatum* responded quadratically to irrigation with the optimum varying by year. The other species tested had insufficient plant stands to reliably evaluate their response to irrigation.

Management Applications

The report above describes practices that can be immediately implemented by seed growers. A multi-year summary of research findings is found in Table 7.

Table 4. Precipitation and growing degree-days at the Malheur Experiment Station, Ontario, OR.

	Precipitation (inches)		Growing degree-days (50-86°F)
Year	Jan-June	April-June	Jan-June
2006	9.0	3.1	1120
2007	3.1	1.9	1208
2008	2.9	1.2	936
2009	5.8	3.9	1028
2010	8.3	4.3	779
2011	8.3	3.9	671
66-year average	5.8	2.7	1042[a]

[a]25-year average.

Table 5. Native forb seed yield response to irrigation rate (inches/season) in 2006, 2007, and 2008. Malheur Experiment Station, Oregon State University, Ontario, OR.

Species	2006				2007				2008			
	0 inches	4 inches	8 inches	LSD (0.05)	0 inches	4 inches	8 inches	LSD (0.05)	0 inches	4 inches	8 inches	LSD (0.05)
	---------- lb/acre ----------											
Eriogonum umbellatum[a]	155.3	214.4	371.6	92.9	79.6	164.8	193.8	79.8	121.3	221.5	245.2	51.7
Penstemon acuminatus[a]	538.4	611.1	544.0	NS	19.3	50.1	19.1	25.5[b]	56.2	150.7	187.1	79.0
Penstemon deustus[c]	1246.4	1200.8	1068.6	NS	120.3	187.7	148.3	NS	--- very poor stand ---			
Penstemon speciosus[a]	163.5	346.2	213.6	134.3	2.5	9.3	5.3	4.7[b]	94.0	367.0	276.5	179.6
Lomatium dissectum[d]	---- no flowering ----				--- no flowering ---				--- very little flowering ---			
Lomatium triternatum[d]	---- no flowering ----				2.3	17.5	26.7	16.9[b]	195.3	1060.9	1386.9	410.0
Lomatium grayi[d]	---- no flowering ----				36.1	88.3	131.9	77.7[b]	393.3	1287.0	1444.9	141.0
Sphaeralcea parvifolia[e]					1062.6	850.7	957.9	NS	436.2	569.1	544.7	NS
Sphaeralcea grossulariifolia[e]					442.6	324.8	351.9	NS	275.3	183.3	178.7	NS
Sphaeralcea coccinea[e]					279.8	262.1	310.3	NS	298.7	304.1	205.2	NS
Dalea searlsiae[e]					11.5	10.2	16.4	NS	----- very poor stand ----			
Dalea ornata[e]					47.4	27.3	55.6	NS	----- very poor stand ----			

[a] planted March, 2005, areas of low stand replanted by hand in October 2005.
[b] LSD (0.10).
[c] planted March, 2005, areas of low stand replanted by hand in October 2005 and whole area replanted in October 2006. Yields in 2006 are based on small areas with adequate stand. Yields in 2007 are based on whole area of very poor and uneven stand.
[d] planted March, 2005, whole area replanted in October 2005.
[e] planted spring 2006, whole area replanted in November 2006.

Table 6. Native forb seed yield response to irrigation rate (inches/season) in 2009, 2010, 2011, and 2- to 6-year averages. Malheur Experiment Station, Oregon State University, Ontario, OR.

Species	2009				2010				2011			
	0 inches	4 inches	8 inches	LSD (0.05)	0 inches	4 inches	8 inches	LSD (0.05)	0 inches	4 inches	8 inches	LSD (0.05)
	lb/acre											
Eriogonum umbellatum[a]	132.3	223	240.1	67.4	252.9	260.3	208.8	NS	248.7	136.9	121.0	90.9
Penstemon acuminatus[a]	20.7	12.5	11.6	NS	--- Stand disked out ---							
Penstemon speciosus[a]	6.8	16.1	9	6.0b	147.2	74.3	69.7	NS	371.1	328.2	348.6	NS
Lomatium dissectum[d]	50.6	320.5	327.8	196.4b	265.8	543.8	499.6	199.6	567.5	1342.8	1113.8	180.9
Lomatium triternatum[d]	181.6	780.1	676.1	177	1637.2	2829.6	3194.6	309.4	1982.9	2624.5	2028.1	502.3[f]
Lomatium grayi[d]	359.9	579.8	686.5	208.4	1035.7	1143.5	704.8	NS	570.3	572.7	347.6	NS
Sphaeralcea parvifolia[e]	285.9	406.1	433.3	NS	245.3	327.3	257.3	NS	81.6	142.5	141.2	NS
Sphaeralcea grossulariifolia[e]	270.7	298.9	327	NS	310.5	351	346.6	NS	224.0	261.9	148.1	NS
Sphaeralcea coccinea[e]	332.2	172.1	263.3	NS	385.7	282.6	372.5	NS	89.6	199.6	60.5	NS

Species	2- to 6-year averages			
	0 inches	4 inches	8 inches	LSD (0.05)
Eriogonum umbellatum[a]	173.4	200.7	224.8	34.5
Penstemon acuminatus[a]	163.8	204.8	189.9	NS
Penstemon speciosus[a]	131.8	179.8	153.5	NS
Lomatium dissectum[d]	294.6	691.0	647.1	195.7
Lomatium triternatum[d]	799.8	1462.5	1462.5	200.9
Lomatium grayi[d]	479.0	734.3	663.1	160.7[b]
Sphaeralcea parvifolia[e]	449.9	495.9	495.8	NS
Sphaeralcea grossulariifolia[e]	339.5	323.4	309.4	NS
Sphaeralcea coccinea[e]	320.5	275.8	284.2	NS

[a] planted March, 2005, areas of low stand replanted by hand in October 2005.
[b] LSD (0.10).
[c] planted March, 2005, areas of low stand replanted by hand in October 2005 and whole area replanted in October 2006. Yields in 2006 were based on small areas with adequate stand. Yields in 2007 were based on whole area of very poor and uneven stand.
[d] planted March, 2005, whole area replanted in October 2005.
[e] planted spring 2006, whole area replanted in November 2006.

Table 7. Amount of irrigation water for maximum native wildflower seed yield, years to seed set, and life span. A summary of multi-year research findings, Malheur Experiment Station, Oregon State University, Ontario, OR.

Species	Optimum amount of irrigation	Years to first seed set	Life span
	inches/season	from fall planting	years
Eriogonum umbellatum	0 in wet years, 7 to 8 in dry years	1	6+
Penstemon acuminatus	no response	1	3
Penstemon speciosus	0 in wet years, 4 in dry years	1	3
Lomatium dissectum	6	4	6+
Lomatium triternatum	4 to 8 depending on precipitation	2	6+
Lomatium grayi	0 in wet years, 7 to 8 in dry years	2	6+
Sphaeralcea parvifolia	no response	1	5+
Sphaeralcea grossulariifolia	no response	1	5+
Sphaeralcea coccinea	no response	1	5+

Hydraulic Consideration for SDI Systems

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***Abstract*.** Subsurface drip irrigation (SDI) systems are increasingly being used for grain and fiber crops which have much less income potential than fruit, vegetable, vine and tree crops. These systems when used on the lesser value crops are typically have a deeper installation and are intended for multiple years of usage without replacement. As with any irrigation system, SDI must be designed with careful consideration of the hydraulic requirements, but the SDI system longevity must also be carefully considered when being used for lower value crops that need many years to amortize the initial cost. Longer length driplines are generally desirable for these SDI systems being used for lower value crops because that reduces the system cost and may reduce the irrigation management time. Because the systems are being used for many years without replacement, careful consideration must be given to the flushing requirements.

Keywords. microirrigation, subsurface drip irrigation, irrigation design

Introduction

A guiding principle in microirrigation design is to obtain and maintain high water application uniformity along the length of the driplines. Dripline and emitter characteristics and hydraulic properties, system operating pressure, and land slope are the major governing factors controlling the hydraulic design. 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 typically grown in the Great Plains. Additionally, longevity of SDI systems is affected by how well the system is maintained and periodic flushing with a sufficient flushing velocity is considered an important aspect of routine maintenance.

Hydraulic Considerations for Dripline Length

Many different design criteria and procedures are used to calculate the maximum dripline length. Two uniformity criteria often used in microirrigation design are emitter discharge variation, q_{var}, and design emission uniformity, *EU,* and are given by

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \qquad \text{(Eq. 1)}$$

and

$$EU = 100\left[1.0 - \frac{1.27\,CV}{\sqrt{n}}\right]\frac{q_{min}}{q_{avg}} \qquad \text{(Eq. 2)}$$

where q_{max}, q_{min}, and q_{avg}, are the maximum, minimum, and average emitter discharge rates (gal/hr), respectively, along the dripline, *EU* is the design emission uniformity, n is the number of drip emitters per plant or 1, whichever is greater, and *CV* is the manufacturer's coefficient of variation.

Emitter flow variation of 10% or less is generally desirable, between 10% and 20% is acceptable, and greater than 20% is unacceptable (Bralts et al., 1987). Design emission uniformities of 80 to 90 are recommended for line-source emitters on uniform slopes and 70 to 85 on steep or undulating slopes (ASAE EP405.1, 2010). It should be noted that the use of these recommended q_{var} and *EU* criteria produce different results. Both criteria are reasonable for design purposes, however, and interrelationships exist for many of the design criteria used in microirrigation. Other hydraulic design procedures are available (Burt and Styles, 2007) and many of the dripline manufacturers provide their own software programs for system design. Some of these software programs will be used in this discussion to demonstrate important factors related to dripline design.

Emitter flow variation increases and design emission uniformity decreases as the emitter discharge rate and dripline length increase (Figure 1). In this example, for a 0.785 inside diameter *(ID)* dripline and dripline lengths of 500, 750, or 1000 feet, only four options have q_{var} values less than 10%, the 500 ft length with any of the emitter discharge rates and the 750 ft length for the 0.20 g/h emitter discharge rate. The acceptable 20% q_{var} criterion allows more acceptable emitter discharge and length combinations. Figure 1 also illustrates some discrepancy in the acceptable ranges between the q_{var} and *EU* design criteria, with a larger number of emitter discharge rate and length combinations providing an acceptable *EU.* There has been discussion among irrigation engineers that the ASABE EP405.1 design emission uniformity criteria for line-source emitters may need to be increased to values similar to those for point-source emitters. Manufacturing processes for line-source emitters have improved over the years and lower *EU* values for these products may no longer be necessary. A portion of the rationale for allowing reduced *EU* for line-source products is related to the typical single-year use of these products for DI where the long-term effects (season to season) of reduced uniformity would not occur. Thus, greater *EU* values may have more importance for multiple-year SDI systems.

Longer driplines with higher uniformity can be designed by increasing the dripline diameter while holding the emitter discharge constant (Figure 2). This design technique is popular for larger SDI systems used on the lower-valued commodity crops (fiber, grains and oilseeds) because it helps 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 (Figure 3), and flushing flowrates can become quite large. 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. Figure 3 also illustrates that chemigation travel times are not greatly affected by dripline length (slight increases with increase length), are moderately affected by emitter discharge (moderate decrease with increased emitter discharge), and are strongly affected by dripline diameter (major increases with increased diameter).

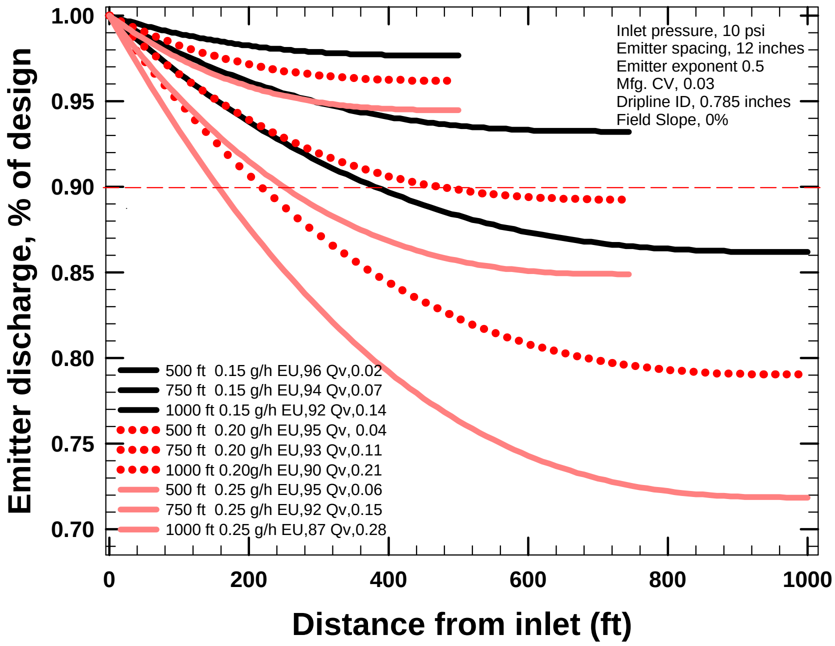

Figure 1. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by dripline length and nominal design emitter discharge. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

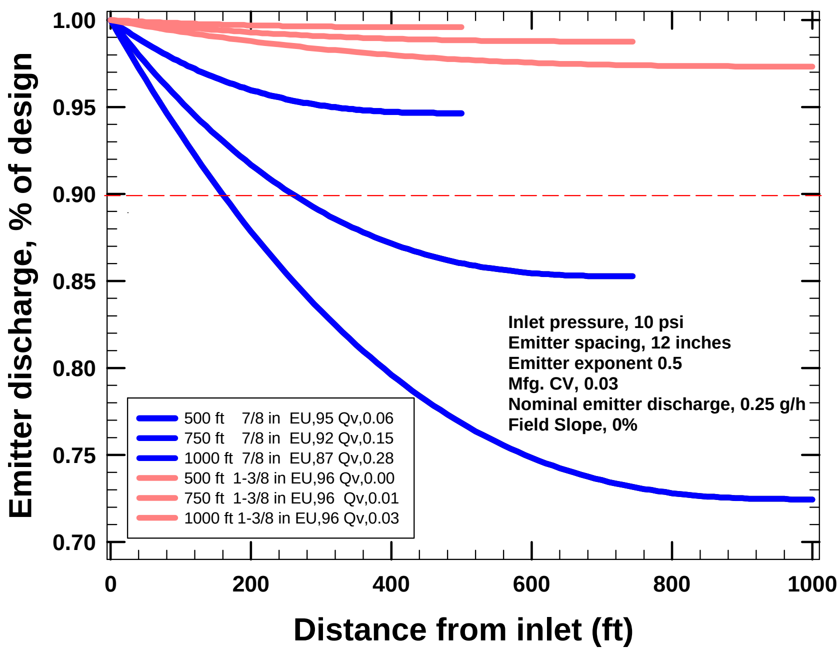

Figure 2. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by dripline length and inside diameter. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

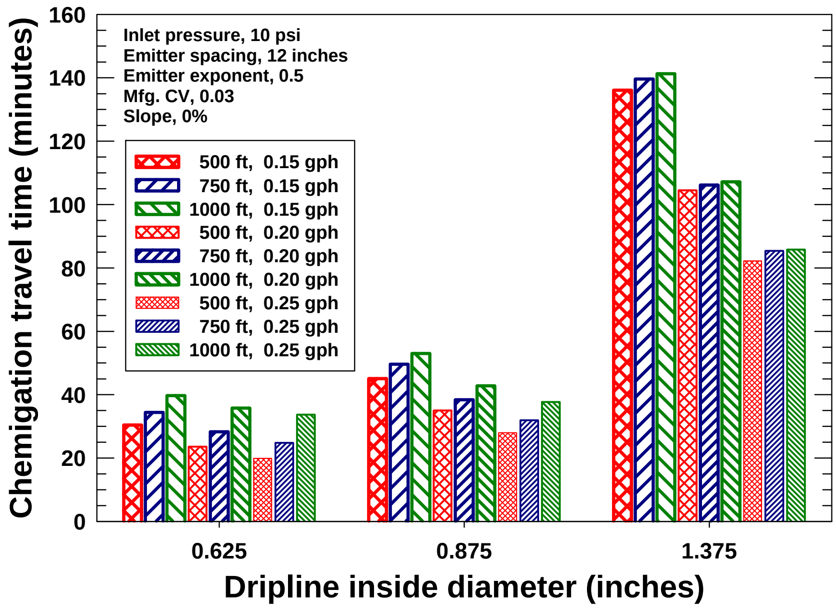

Figure 3. Approximate chemigation travel times as affected by dripline length and diameter, and emitter discharge rate. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

While maintaining system uniformity, dripline length can also be increased by increasing the emitter spacing while holding the emitter discharge rate constant (Figure 4). This is also a popular design technique for larger SDI systems used on lower-valued crops, but is limited because the emitter spacing must be consistent with uniform water uptake by the crop. Emitter spacing may become too great as random emitters begin to clog.

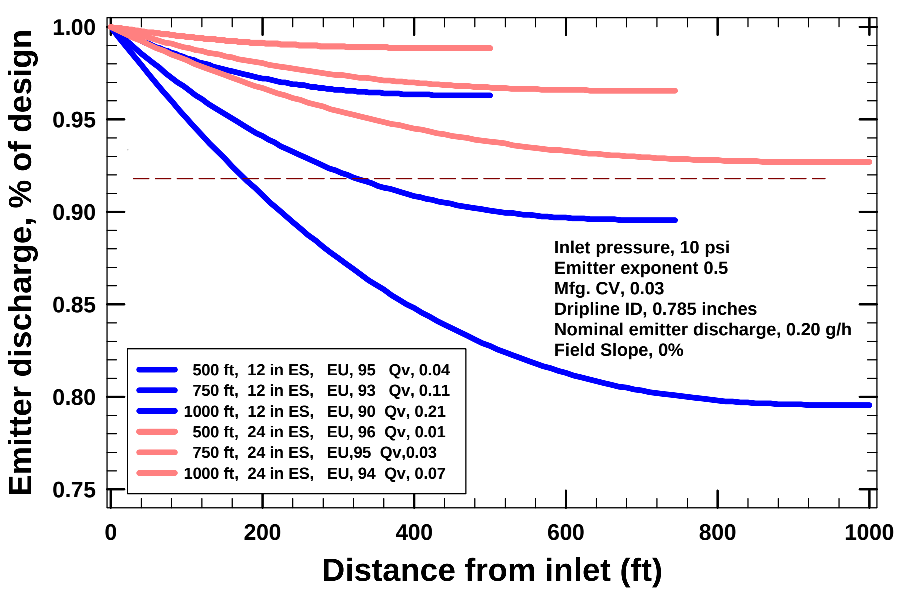

Figure 4. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by dripline length and emitter spacing *(ES)*. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

The land slope can have either a positive or negative effect on the emitter discharge rate along the dripline lateral (Figure 5). Driplines running uphill always result in increasing pressure losses along the dripline and thus lower system uniformity. When the downhill slope is too great, the emitter discharge rate at the end of the dripline becomes unacceptably high. In the example shown (Figure 5), the optimum slope is 1% downslope, but this will vary with dripline and emitter characteristics. Designers may even use these hydraulic factors to their advantage to balance elevation head gains with increased friction losses from smaller diameter driplines. When slopes are too great, designers may recommend that the driplines be installed across the slope or along the contour.

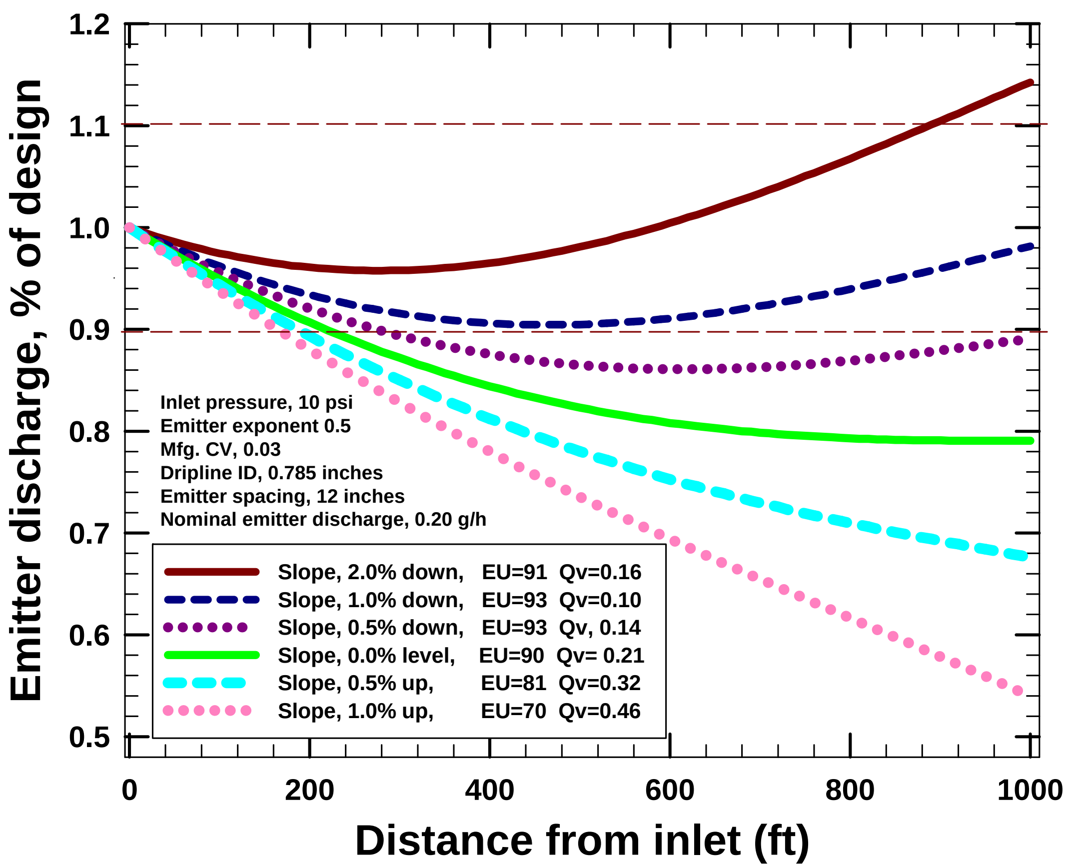

Figure 5. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by topography. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

The emitter discharge (q) can generally be characterized by a simple power equation

$$q = kH^x \qquad \text{(Eq. 3)}$$

where k is a constant depending upon the units of q and H, H is the pressure and x is the emitter exponent. The value of x is typically between 0 and 1, although values outside the range are possible. For an ideal product, x equals 0, meaning that the emitter discharge is independent of the pressure. This would allow for high uniformity on very long driplines, which would minimize cost (Figure 6). An emission product with an x of 0 is said to be fully pressure compensating (PC). An x value of 1 is noncompensating (NPC), meaning any percentage change in pressure results in an equal percentage change in emitter discharge rate. Many lay-flat dripline products have an emitter exponent of approximately 0.5. A 20% change in pressure along the dripline results in a 10% change in emitter discharge rate if the exponent is 0.5. Pressure-compensating emitters are widely used on steep land slopes, but are not always cost-competitive for lower-valued commodity crops.

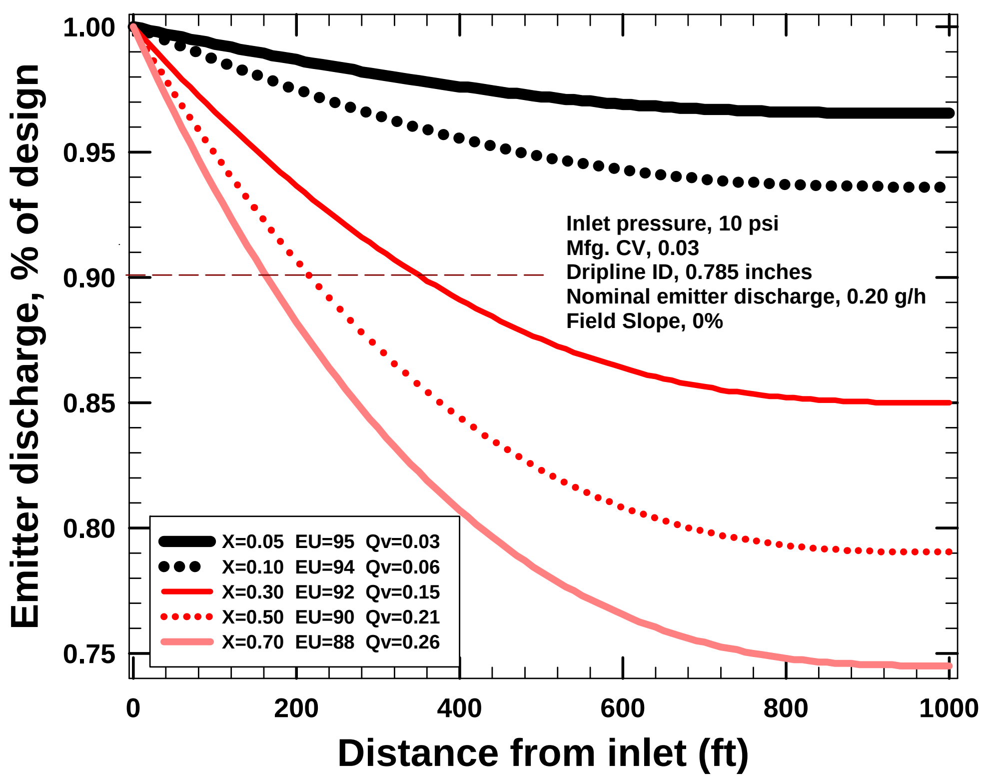

Figure 6. Calculated emitter discharge, emission uniformity (EU), and emitter discharge variation (q_{var}) as affected by the emitter exponent (x). An emitter with an exponent of zero is said to be fully pressure compensating (PC). Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

Hydraulic Considerations for Flushing Velocity

A minimum flushing velocity of 1 ft/s is recommended for microirrigation systems by the American Society of Biological and Agricultural Engineers (ASAE EP405.1, 2003). However, disagreement exists about the recommended flushing velocity for SDI systems, with values ranging from 1 to 2 ft/s (Burt and Styles, 2007). The practical rationale for a higher flushing velocity for SDI is that perhaps it could provide better overall flushing of materials. Many of these systems are used for multiple years and system longevity is very important in determining SDI economic feasibility, especially for lower-valued crops. The required flushing velocity and flushline hydraulics greatly affect the SDI system design. Higher velocities require large supply lines and flushlines and shorter lengths of run to keep the flushing pressures below the maximum allowable dripline operating pressure. The general guideline is that the required flushing velocity be maintained in all segments of the SDI system, but there are locations where this guideline cannot be followed. The water velocity in the flushline at the farthest point from the flush valve is very low because only a single dripline is contributing flow. Decreasing the flushline diameter at this point in the system could help maintain a higher velocity but also increases the downstream pressure on the dripline. It is more important to maintain adequate flushing velocity in the driplines because the emitters are subject to clogging.

Some pressure usually exists on the end of driplines during flushing for SDI systems that use a flushline common to a group of driplines. This downstream pressure represents the sum of elevation changes between the dripline and the point where the water exits the flush valve, friction losses in the flushline, friction losses in the flush valve, and the friction losses associated with the dripline/flushline connection. It is difficult to design for a dripline downstream pressure during flushing of less than 1 psi and values of 3 psi are reasonable under some circumstances. Downstream pressures that are greater than 3 psi during flushing will often require driplines with higher maximum allowable operating pressure or that the designer must reduce dripline length and/or emitter discharge rates. The inlet pressure during flushing often has more restriction on design dripline length and emitter discharge rate than system uniformity (Figure 7). Adjustable pressure regulators or other design characteristics may be required to accommodate the higher inlet pressure requirements during flushing.

The required flowrate during flushing can be considerably higher than the nominal dripline flowrate (Figure 8). This may require larger pipe size (mains, submains and headers), adjustments to the pumping plant to provide the larger flow, and/or splitting the normal irrigation zone into more than one flushing zone.

Conclusions

Careful consideration must be given to the hydraulic design of SDI systems because of the complex manner in which the different factors interact. An improperly designed SDI system is less forgiving than an improperly designed center pivot sprinkler system. Water distribution problems may be difficult or impossible to correct for an improperly designed SDI system. The SDI system must also be properly designed to ensure system longevity. Minimizing investment costs through cheaper designs can be a double-edged sword, as a cheaper system may increase operating costs and/or possibly increase the chance of system failure.

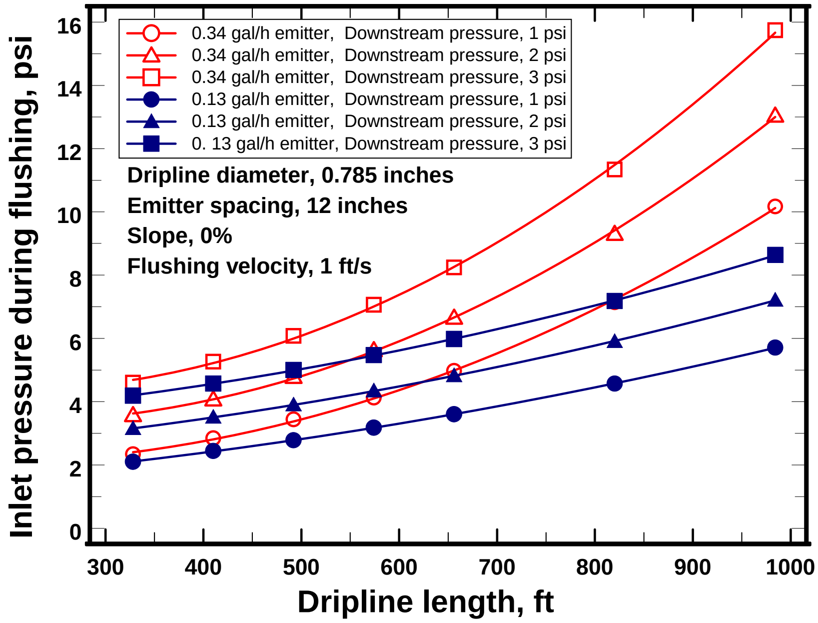

Figure 7. Required inlet pressure to maintain a 1 ft/s dripline flushing velocity, as affected by the nominal emitter discharge rate, dripline length, and downstream pressure. Results for hypothetical dripline calculated with software from Toro Ag Irrigation (2002).

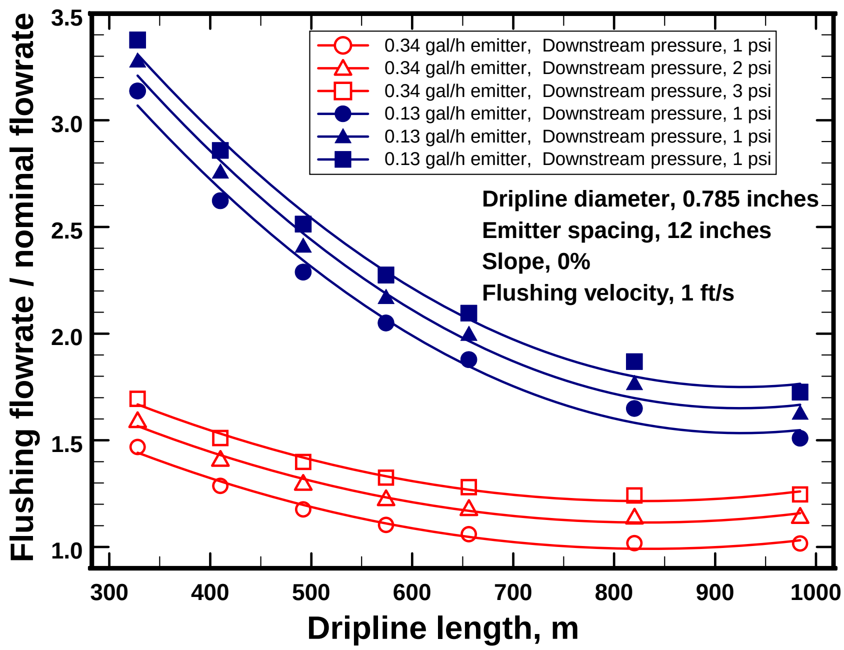

Figure 8. Ratio of required flushing flowrate to nominal design flowrate to maintain a 1 ft/s dripline flushing velocity as affected by nominal emitter discharge rate, dripline length, and downstream pressure. Results for hypothetical dripline calculated using software from Toro Ag Irrigation (2002).

Acknowledgements

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

This paper is also part of an SDI technology transfer effort beginning 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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Comparison of SDI and Center Pivot Sprinkler Economics

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***Abstract*.** Although center pivot sprinkler irrigation (CP) is the predominant irrigation method in the US Great Plains, there is growing interest in the use of subsurface drip irrigation (SDI). Pressurized irrigation systems, in general, are a costly investment and this is particularly the case with subsurface drip irrigation (SDI). Producers need to carefully determine their best investment options. In 2002, Kansas State University developed a free Microsoft Excel template to compare the economics of center pivot sprinkler irrigation and subsurface drip irrigation for field corn (maize) production. This template has been updated annually with new input and revenue costs and assumptions. Important factors that have always affected CP and SDI competitiveness are field size and shape suitable for center pivot sprinkler irrigation and longevity of SDI system allowing longer amortization of its greater initial cost. The primary factors that allow SDI to have greater economic competiveness than was the case in 2002 are greater corn yields and corn price. Using the base assumptions in the template for a square 160 acre field, an SDI system lasting at least 11 years can be cost competitive with a center pivot sprinkler with a life of 25 years.

Keywords. microirrigation, economics, sprinkler irrigation, revenue.

Introduction

In much of the Great Plains, the rate of new irrigation development is slow or zero. Although the Kansas irrigated area, as reported by producers through annual irrigation water use reports, has been approximately 3 million acres since 1990, there has been a dramatic shift in the methods of irrigation. During the period since 1990, the number of acres irrigated by center pivot irrigation systems increased from about 50 per cent of the total irrigated acreage base to about 90 percent of the base area.

In 1989, subsurface drip irrigation (SDI) research plots were established at Kansas State University Research Stations to investigate SDI as a possible additional irrigation system option. Early industry and producers surveys have indicated a small but steady increase in adoption. Field area as reported by the 2006 Kansas Irrigation Water Use Report indicated that 10,250 acres were exclusively irrigated by SDI systems and an additional 8,440 acres were irrigated partly by SDI in combination with another system type such as an irrigated SDI corner of a center pivot sprinkler or a surface gravity-irrigated field partially converted to SDI. Although Kansas SDI systems represent less than 1 percent of the irrigated area, producer interest still remains high because SDI can potentially have higher irrigation efficiency and irrigation uniformity. As the farming populace and irrigation systems age, there will likely be a continued momentum for conversion to modern pressurized irrigation systems. Both center pivot sprinkler irrigation (CP) and subsurface drip irrigation (SDI) are options available to the producer for much of the Great Plains landscape (low slope and deep silt loam soils). Pressurized irrigation systems in general are a costly investment and this is particularly the case with SDI. Producers need to carefully determine their best investment options.

In the spring of 2002, a free Microsoft Excel[1] spreadsheet template was introduced by K-State Research and Extension for making economic comparisons of CP and SDI. Since that time, the spreadsheet has been periodically updated to reflect changes in input data, particularly system and corn production costs. The spreadsheet also provides sensitivity analyses for key factors. This paper will discuss how to use the spreadsheet and the key factors that most strongly affect the comparisons. The 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).

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 12.3, modified by F.R. Lamm, D. M. O'Brien, D. H. Rogers, T. J. Dumler, 10-06-12

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 $			$71,815	← $71,815	$202,617	← $202,617
Irrigation system investment cost, $/irrigated acre			$574.52		$1,307.21	
Irrigation system life, years			25	← 25	22	← 22
Interest rate for system investment, %	6.5%	← 6.5%				
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)			$617.56	← $617.56	$600.63	← $600.63
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	$5.75	← $5.75				
Net return to cropped dryland area of field ($/acre)	$64.00	← $36.00				
Advantage of SDI over Center Pivot Sprinkler *					**$/total field each year**	**$9,472**
*** Advantage in net returns to land and management**					**$/acres each year**	**$59**

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.

Analyses Methods and Economic Assumptions

There are 18 required input variables required to use the spreadsheet template, but if the user does not know a particular value there are suggested values for each of them. The user is responsible for entering and checking the values in the unprotected input cells. All other cells are protected on the Main worksheet (tab). Some error checking exists on overall field size and some items (e.g. overall results and cost savings) are highlighted differently when different results are indicated. Details and rationales behind the input variables are given in the following sections.

Field & irrigation system assumptions and estimates

Many of the early analyses assumed that an existing furrow-irrigated field with a working well and pumping plant was being converted to either CP or SDI and this still may be the base condition for some producers. However, the template can also be used to consider options for a currently center pivot irrigated field that needs to be replaced. The major change in the analysis for the replacement CP is that the cost for the new center pivot probably would not have to include buried underground pipe and electrical service in the initial investment cost. The analysis also assumes the pumping plant is located at the center of one of the field edges and is at a suitable location for the initial SDI distribution point (i.e. upslope of the field to be irrigated). Any necessary pump modifications (flow and pressure) for the CP or SDI systems are assumed to be of equal cost and thus are not considered in the analysis. However, they can easily be handled as an increased system cost for either or both of the system types.

Land costs are assumed to be equal across systems for the overall field size with no differential values in real estate taxes or in any government farm payments. Thus, these factors “fall out” or do not economically affect the analyses.

An overall field size of 160 acres (square quarter section) was assumed for the base analysis. This overall field size will accommodate either a 125 acre CP system or a 155 acre SDI system. It was assumed that there would be 5 noncropped acres consumed by field roads and access areas. The remaining 30 acres under the CP system are available for dryland cropping systems.

Irrigation system costs are highly variable at this point in time due to rapid fluctuations in material and energy costs. Cost estimates for the 125 acre CP system and the 155 acre SDI system are provided on the current version of the spreadsheet template based on discussions with dealers and O’Brien et al. (2011), but since this is the overall basis of the comparison, it is recommended that the user apply his own estimates for his conditions. In the base analyses, the life for the two systems is assumed to be 25 and 22 years for the CP and SDI systems, respectively. No salvage value was assumed for either system. This assumption of no salvage value may be inaccurate, as both systems might have a few components that may be reusable or available for resale at the end of the system life. However, with relatively long depreciation periods of 22 and 25 years and typical financial interest rates, the zero salvage value is a very minor issue in the analysis. System life is a very important factor in the overall analyses. However, the life of the SDI system is of much greater economic importance in analysis than a similar life for the CP system because of the much higher system costs for SDI. Increasing the system life from 22 to 25 years for SDI would have a much greater economic effect than increasing the CP life from 22 to 25 years.

When the overall field size decreases, thus decreasing system size, there are large changes in cost per irrigated acre between systems. SDI costs are nearly proportional to field size, while CP costs are not proportional to field size (Figure 2). Quadratic equations were developed to calculate system costs when less than full size 160 acre fields were used in the analysis (Obrien et al., 1998):

$$CPcost\% = 44.4 + (0.837 \times CPsize\%) - (0.00282 \times CPsize\%^2) \qquad \text{(Eq. 1)}$$

$$SDIcost\% = 2.9 + (1.034 \times SDIsize\%) - (0.0006 \times SDIsize\%^2) \qquad \text{(Eq. 2)}$$

where CPcost% and CPsize%, and SDIcost% and SDIsize% are the respective cost and size % in relation to the full costs and sizes of irrigation systems fitting within a square 160 acre block.

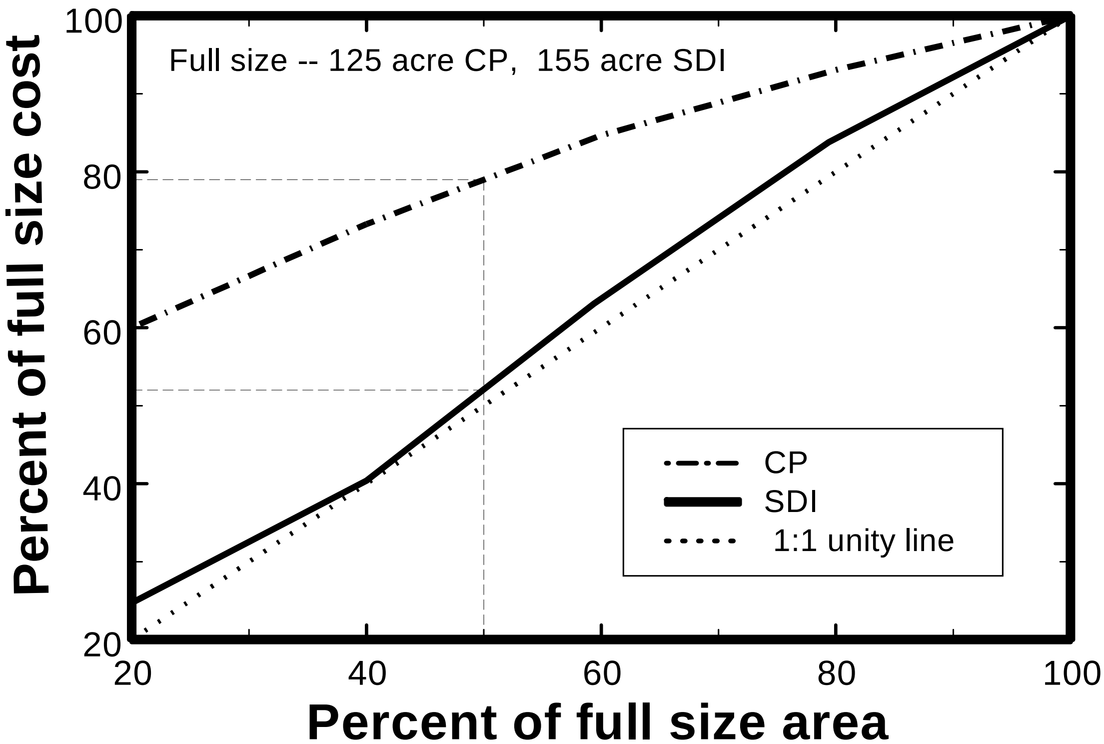

Figure 2. CP and SDI system costs as related to field size. (after O'Brien et al., 1998)

The annual interest rate can be entered as a variable, but is currently assumed to be 6.5%. The total interest costs over the life of the two systems were converted to an average annual interest cost for this analysis. Annual insurance costs were assumed to be 1.6% of the total system cost for the center pivot sprinkler and 0.6% for the SDI system, but can be changed if better information is available. The lower value for the SDI was based on the assumption that only about 40% of the system might be insurable. Many of the SDI components are not subject to the climatic conditions that are typically insured hazards for CP systems. However, system failure risk is probably greater with SDI systems which might influence any obtainable insurance rate. The cost of insurance is a minor factor in the economic comparison when using the current values.

Production cost assumptions and estimates

The economic analysis expresses the results as an advantage of SDI or alternatively CP systems in net returns to land and management. Thus, many fixed costs do not affect the analysis and can be ignored. Additionally, the analysis does not indicate if either system is ultimately profitable for corn production under the assumed current economic conditions.

Production costs were adapted from KSU estimates (Dumler et al., 2011). A listing of the current costs is available on the CF worksheet (tab) (Figure 3) and the user can enter new values to recalculate variable costs that more closely match their conditions. The sum of these costs would become the new suggested Total Variable Costs on the Main worksheet (tab), but the user must manually change the input value on the Main worksheet (White input cell box) for the economic comparison to take effect. The user may find it easier to just change the differential production costs between the systems on the Main tab rather than changing the baseline assumptions on the CF tab. This will help maintain integrity of the baseline production cost assumptions.

Factors for Variable Costs			**CP**	**Suggested**	**SDI**	**Suggested**
Seeding rate, seeds/acre	$/1000 S	**Suggested**	34000	← 34000	34000	← 34000
Seed, $/acre	$2.89	← $2.89	$98.26		$98.26	
Herbicide, $/acre			$26.20	← $26.20	$26.20	← $26.20
Insecticide, $/acre			$36.48	← $36.48	$36.48	← $36.48
Nitrogen fertilizer, lb/acre	$/lb	**Suggested**	242	← 242	242	← 242
Nitrogen fertilizer, $/acre	$0.44	← $0.44	$106.48		$106.48	
Phosphorus fertilizer, lb/acre	$/lb	**Suggested**	50	← 50	50	← 50
Phosphorus fertilizer, $/acre	$0.80	← $0.80	$40.00		$40.00	
Crop consulting, $/acre			$6.50	← $6.50	$6.50	← $6.50
Crop insurance, $/acre			$33.00	← $33.00	$33.00	← $33.00
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			$175.00	← $175.00	$175.00	← $175.00
Other non-fieldwork labor, $/acre			$0.00	← $0.00	$0.00	← $0.00
Irrigation labor, $/acre			$6.50	← $6.50	$6.50	← $6.50
Irrigation amounts, inches			17	← 17	13	← 13
Fuel and oil for pumping, $/inch			$3.50	← $3.50	$3.50	← $3.50
Fuel and oil for pumping, $acre			$59.50		$45.50	
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	6.5%	← 6.5%	$19.44		$18.91	
Total Variable Costs			**$617.56**		**$600.63**	

Figure 3. CF worksheet (tab) of the economic comparison spreadsheet template and the current production cost variables. Note that the sums at the bottom of the CF worksheet are the suggested values for total variable costs on the Main worksheet (tab).

The reduction in variable costs for SDI is attributable to an assumed 25% net water savings that is consistent with research findings by Lamm et al. (1995). This translates into a 17 and 13 inch gross application amount for CP and SDI, respectively. The current estimated production costs are somewhat high reflecting increased energy and other related input costs, but fortunately crop revenues have also increased due to high demand for corn for ethanol production. This fact is pointed out because a lowering of overall variable costs favors SDI, since more irrigated cropped acres are involved, while higher overall variable costs favors CP production. The variable costs for both irrigation systems represent typical practices for western Kansas.

Yield and revenue stream estimates

Corn grain yield is currently estimated at 220 bushels/acre in the base analysis with a corn price of $5.75/bushel (See values on Main worksheet). Net returns for the 30 cropped dryland acres for the CP system (corners of field) were assumed to be $64.00/acre which is essentially the current dryland crop cash rent estimate for Northwest Kansas. Government payments related to irrigated crop production are assumed to be spread across the overall field size, and thus, do not affect the economic comparison of systems.

Sensitivity Analyses

Changes in the economic assumptions can drastically affect which system is most profitable and by how much.

Previous analyses have shown that the system comparisons are very sensitive to assumptions about

- 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 very sensitive to

- any additional production cost savings with SDI.

The results are moderately sensitive to

- corn yield
- corn price
- yield/price combinations

and the results are very sensitive to

- higher potential yields with SDI

with advantages favoring SDI as corn yields and price increase.

The economic comparison spreadsheet also includes three worksheet (tabs) that display tabular and graphical sensitivity analyses for field size and SDI system life (Figure 4), SDI system cost and life (Figure 5), and corn yield and selling price (Figure 6). These sensitivity analysis worksheets will automatically update when different assumptions are made on the Main worksheet. The elements in light blue of the sensitivity tables indicate cases where CP systems are more profitable while elements with negative signs in reddish brown are cases where SDI is more profitable.

This tab determines the CP and SDI economic sensitivity to field size, shape, and SDI system life.

The elements in the table (blue) represent the CP advantage in net returns per acre.

Field size	160	127	95	64	32	**80**	
CP Size	125	100	75	50	25	**64**	← Wiper 1/2 circle
CP Cost	$574.52	$670.12	$808.81	$1,053.78	$1,723.90	**$1,122.11**	
CP Dry	30	24	18	12	6	**14**	
SDI Size	155	124	93	62	31	78	
SDI Cost	$1,307.21	$1,336.29	$1,367.77	$1,415.05	$1,525.51	$1,387.51	
SDI life years	Note: This sensitivity valid only if full-sized CP (125 acres) and SDI (155 acres) costs exist on Main worksheet (tab) !!!!!!!!						
5	**$136.51**	**$137.69**	**$135.72**	**$128.29**	**$107.48**	**$124.59**	
10	**$9.87**	**$7.22**	**$1.82**	**-$8.80**	**-$40.31**	**-$10.69**	
15	**-$32.34**	**-$36.27**	**-$42.81**	**-$54.49**	**-$89.57**	**-$55.78**	
20	**-$53.45**	**-$58.02**	**-$65.13**	**-$77.34**	**-$114.20**	**-$78.33**	
25	**-$66.11**	**-$71.06**	**-$78.52**	**-$91.05**	**-$128.98**	**-$91.86**	

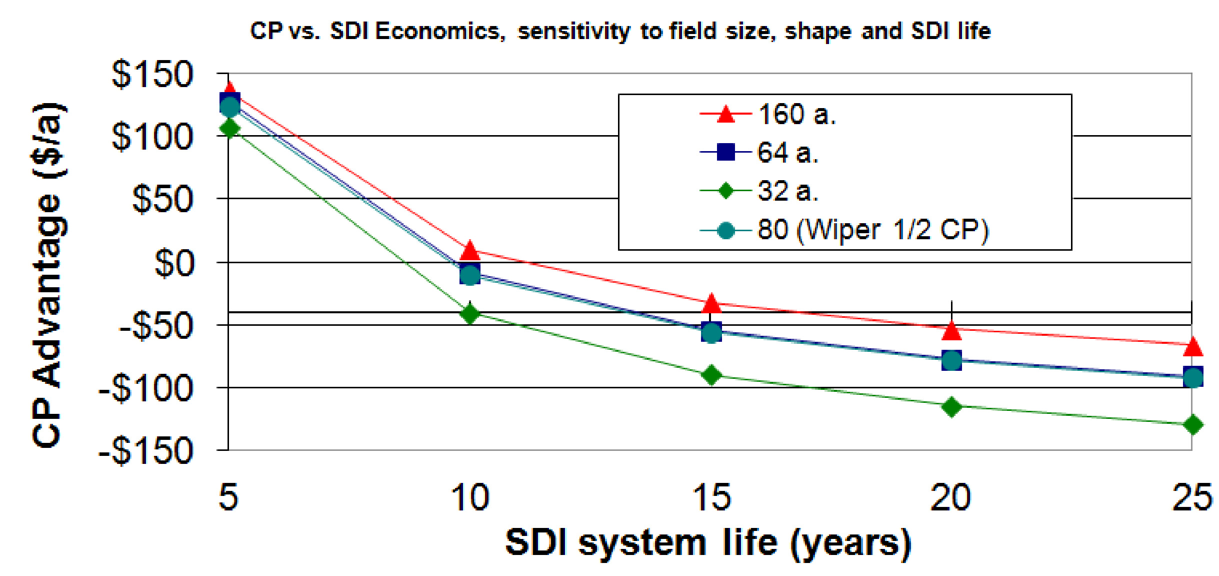

Figure 4. The Field size & SDI life worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

Some Key Observations from Previous Analyses

Users are encouraged to “experiment” with the input values on the Main worksheet (tab) to observe how small changes in economic assumptions can vary the bottom line economic comparison of the two irrigation systems. The following discussion will give the user “hints” about how the comparisons might be affected.

Smaller CP systems and systems which only complete part of the circle are less competitive with SDI than full size 125 acre CP systems This is primarily because the CP investment costs ($/ irrigated acre) increase dramatically as field size decreases (Figure 2 and 4) or when the CP system cannot complete a full circle. It should also be pointed out that part of the economic competitiveness of the higher priced SDI systems with lower priced CP systems occurs simply because less land area of the field is in dryland crop production.

This tab determines the CP and SDI economic sensitivity to SDI system life and SDI system cost.

The elements in the table (blue) represent the CP advantage in net returns per acre.

SDI Cost	SDI system life, years					
$/acre	5	10	15	20	25	30
1000	$65.53	-$31.35	-$63.64	-$79.78	-$89.47	-$95.93
1100	$88.63	-$17.93	-$53.45	-$71.21	-$81.87	-$88.97
1200	$111.74	-$4.51	-$43.26	-$62.64	-$74.26	-$82.01
1300	$134.84	$8.90	-$33.07	-$54.06	-$66.66	-$75.05
1400	$157.95	$22.32	-$22.89	-$45.49	-$59.05	-$68.09
1500	$181.05	$35.74	-$12.70	-$36.92	-$51.45	-$61.14
1600	$204.16	$49.16	-$2.51	-$28.34	-$43.84	-$54.18

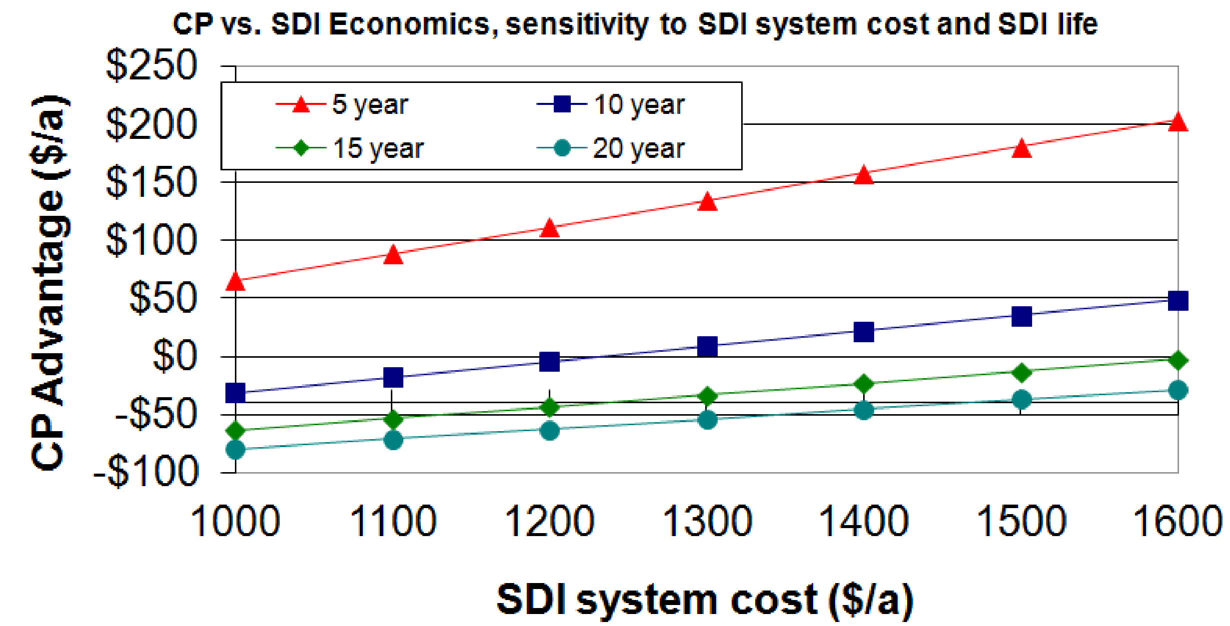

Figure 5. The SDI cost and life worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

Increased longevity for SDI systems is probably the most important factor for SDI to gain economic competitiveness with CP systems. A research SDI system at the KSU Northwest Research-Extension Center in Colby, Kansas has been operated for 22 years with very little performance degradation; so long system life is possible. There are a few SDI systems in the United States that have been operated for over 25 years without replacement (Lamm and Camp, 2007). However, a short SDI system life that might be caused by early failure due to clogging indicates a huge economic disadvantage that would preclude nearly all adoption of SDI systems (Figure 4). Although SDI cost is an important factor, long SDI system life can help reduce the overall economic effect (Figure 5). The CP advantage for SDI system lives between 15 and 20 years is greatly diminished as compared to the difference between 10 and 15 year SDI system life. The sensitivity of CP system life and cost is much less because of the much lower initial CP cost and the much longer assumed life. Changing the CP system life from 25 to 20 years will not have a major effect on the economic comparison. However, in areas where CP life might be much less than 25 years due to corrosive waters, a sensitivity analysis with shorter CP life is warranted.

This tab determines the CP and SDI economic sensitivity to corn yield and corn price assuming that corn yields are equal for both irrigation systems.

The elements in the table (blue) represent the CP advantage in net returns per acre.

	Corn cash price, $/bu						
Corn Yield	**$4.60**	**$5.00**	**$5.40**	**$5.80**	**$6.20**	**$6.60**	**$7.00**
160	$39.99	$27.99	$15.99	$3.99	-$8.01	-$20.01	-$32.01
170	$31.36	$18.61	$5.86	-$6.89	-$19.64	-$32.39	-$45.14
180	$22.74	$9.24	-$4.26	-$17.76	-$31.26	-$44.76	-$58.26
190	$14.11	-$0.14	-$14.39	-$28.64	-$42.89	-$57.14	-$71.39
200	$5.49	-$9.51	-$24.51	-$39.51	-$54.51	-$69.51	-$84.51
210	-$3.14	-$18.89	-$34.64	-$50.39	-$66.14	-$81.89	-$97.64
220	-$11.76	-$28.26	-$44.76	-$61.26	-$77.76	-$94.26	-$110.76
230	-$20.39	-$37.64	-$54.89	-$72.14	-$89.39	-$106.64	-$123.89
240	-$29.01	-$47.01	-$65.01	-$83.01	-$101.01	-$119.01	-$137.01
250	-$37.64	-$56.39	-$75.14	-$93.89	-$112.64	-$131.39	-$150.14
260	-$46.26	-$65.76	-$85.26	-$104.76	-$124.26	-$143.76	-$163.26
270	-$54.89	-$75.14	-$95.39	-$115.64	-$135.89	-$156.14	-$176.39

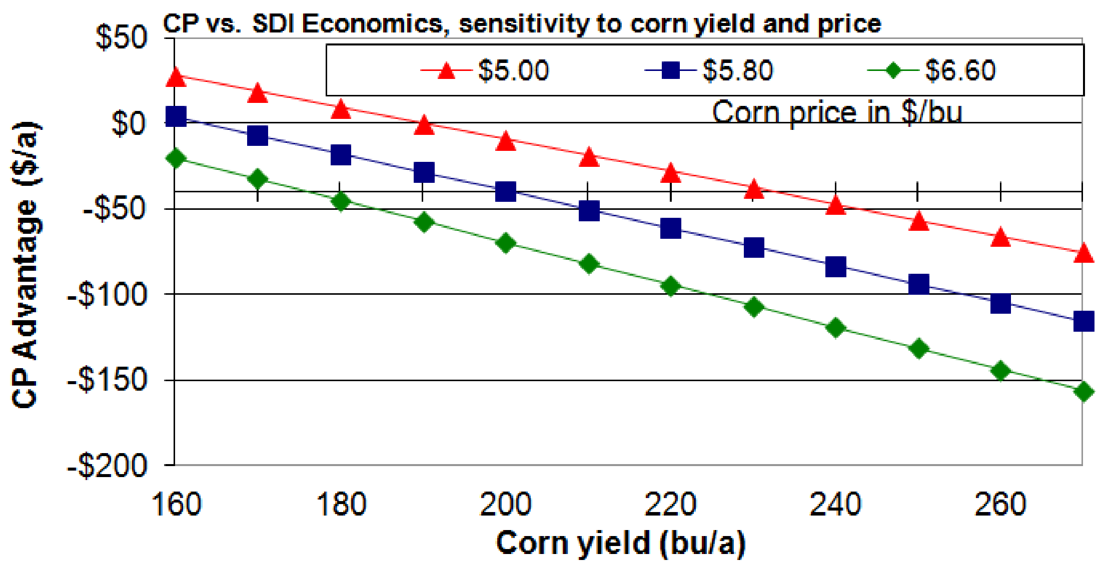

Figure 6. The Yield and Price worksheet (tab) sensitivity analysis. Note this is one of three worksheets (tabs) providing tabular and graphical sensitivity analyses. These worksheets automatically update to reflect changing assumptions on the Main worksheet (tab).

The present baseline analysis already assumes a 25% water savings with SDI. There are potentially some other production cost savings for SDI such as fertilizer and herbicides that have been reported for some crops and some locales. For example, there have been reports from other regions of less broadleaf and grassy weed pressure in SDI where the soil surface remains drier less conducive to germination of weed seeds (Lamm and Camp, 2007). Small changes in the assumptions can make a sizable difference in the economic analysis because there are more irrigated acres under the SDI system.

It has already been stated that higher corn yields and higher corn prices improve the SDI economics. These results can be seen on the Yield and Price sensitivity worksheet (tab) on the Excel template (Figure 6). This result occurs because of the increased irrigated area for SDI in the given 160 acre field. The significance of yield and price can be illustrated by taking one step further in the economic analysis, that being the case where there is a yield difference between irrigation systems. Combining a greater overall corn yield potential with an additional small yield advantage for SDI on the Main tab can allow SDI to be very competitive with CP systems.

Availability of Free Software

A Microsoft Excel spreadsheet template has been developed to allow producers to make their own comparisons. It is available on the SDI economics and software page of the K-State Research and Extension SDI website at http://www.ksre.ksu.edu/sdi/.

Acknowledgements

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

This paper is also part of an SDI technology transfer effort beginning 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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Aerial Thermography for Crop Stress Evaluation

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Abstract. *Foliage temperatures measured in proper context with environmental conditions are sensitive indicators of crop water stress. Aerial thermography of the foliage can provide water stress maps of crops, if properly managed. The challenges of aerial thermography for site specific irrigation are in the measurement and extraction of the relevant canopy temperatures from the thermal image; in determination of the lower and upper temperature limits normalized to ambient conditions; in geo-referencing the results; and in providing useful crop related interpretation. This paper discusses the technology involved.*

Keywords. Site specific irrigation, CWSI, Artificial reference surface, bolometer,

Introduction

The classic crop water stress index (CWSI) introduced by (Jackson, Idso et al. 1981; Idso 1982) became the widely accepted standard for crop water status evaluation from canopy temperature. It is defined as the relation between the actual crop canopy and the reference canopy temperatures of a fully transpiring crop under the same ambient conditions:

Eq. 1. $$CWSI = (T_{canopy} - T_{ref}) / (T_{max} - T_{ref})$$

Where *Tcanopy* is the crop temperature, *Tref* is the reference temperature; *Tmax* is the temperature of a non-transpiring leaf. Ample evidence couples CWSI to other plant stress indicators, like leaf and stem water potential or stomatal conductance, for example (Moller, Alchanatis et al. 2007) and others.

The first challenge of aerial thermography for site specific irrigation is the measurement and extraction of the relevant canopy temperature (*Tcanopy*) from the thermal image by separating the foliage temperature from the soil and from other artifacts. Normalization of foliage temperature to ambient conditions is the second step, i.e., to determine the lower (*Tref*) and upper (*Tmax*) boundaries for CWSI calculation. Ultimately, results should be geo- referenced to crop boundaries, divided into management zones, and the end user should be provided with useful crop related interpretation.

This paper discusses the current methods and technologies involved.

Methods

Measurement and extraction of the relevant canopy temperatures

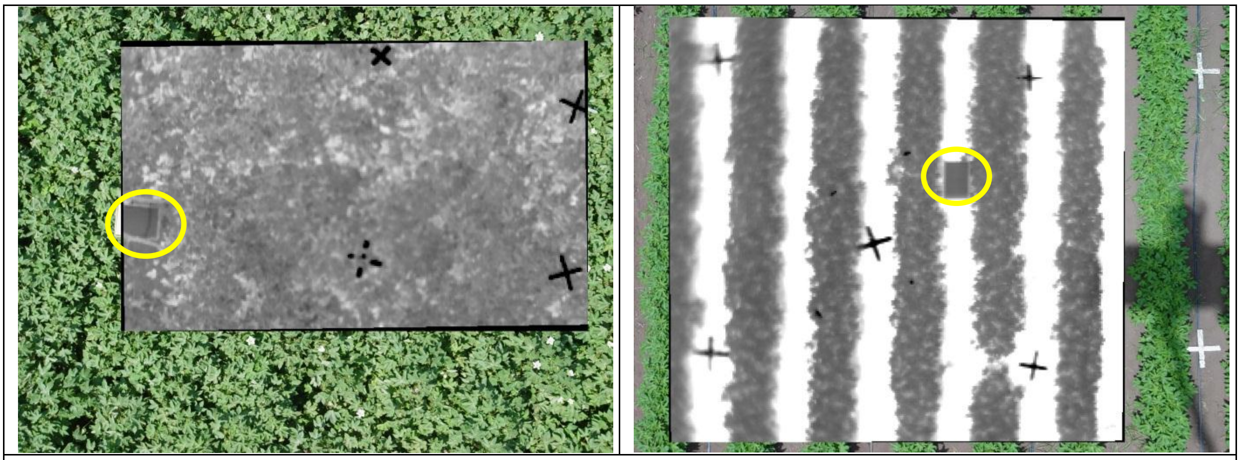

Figure 1. Thermal image overlaid on color picture of fully covered (left) and 0.56 m row width of 0.96 m row spacing (58% cover, right) drip irrigated cotton canopies. Crosses are alignment references, WARS marked with circle. Temperature scale: 19^{o}C (black) to 24.5 ^{o}C (white).

Surface temperatures are never uniform from their nature, even on a single cotton leaf, moreover on a canopy. The examples of seemingly uniform or partially covered cotton canopies (Figure 1.) raise the question:

Where is the relevant *Tcanopy* in the image to use it in the CWSI equation ?

Pixel histograms and statistical filtering can assist in the evaluation. (Meron, Tsipris et al. 2010a)

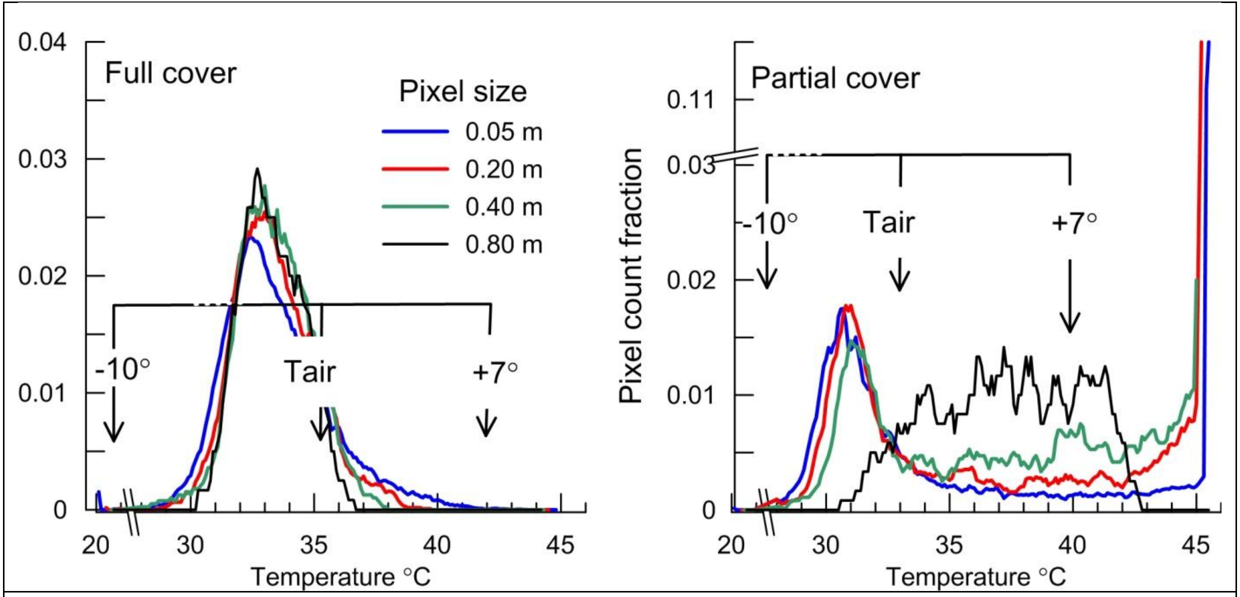

Figure 2. Pixel temperature histograms of fully (left) and 56% covered (right) drip irrigated cotton canopies. Filtering temperatures (Tair-10, Tair, and Tair+7) are marked with black arrows. Axes are broken to allow display of the relevant ranges.

Thermal images from Figure 1 were converted from the original 0.025 m footprints to pixel sizes of 0.05, 0.10, 0.20, 0.40 and 0.80 m/pixel, by averaging four neighboring pixels into one larger pixel size, simulating decreasing resolution of image acquisition. Pixel histograms of both images are shown in Figure 2. The thermal image histogram of a fully covered, uniformly irrigated cotton crop (Figure 2, left) shows Gaussian pixel distribution, in all pixel sizes. In partial canopy cover (Figure 2, right) the Gaussian curve of the colder, foliage related pixels, and the hotter, soil related pixels are discernable up to 0.20 m pixel size. Pixels of 0.80 m size are inherently mixed between soil and foliage, being larger than the 0.58 m cotton canopy width. Large, but smaller than row width, 0.40 m pixels are divided between pure foliage (within the Gaussian distribution) and mixed pixels.

Statistical filtering based on ambient temperature may be applied to eliminate soil and mixed pixels in sparse canopy / partial cover histograms, assuming that leaf temperatures do not exceed *Tair* +7 (Irmak, Haman and Bastug 2000), and pixels below *Tair* -10 are artifacts; example shown in Figure 2. Surface temperature of the colder part of the canopy (*Tcanopy*) can be defined from the filtered data by weighted average of pixels temperature up to predefined thresholds (Figure 3.). In case of full canopy cover filtering and pixel size bear minor effects and filtered or simple population averages are similar. In partial canopy cover filtering and minimizing pixel size are essential to get meaningful data. As a rule of thumb, the optimal pixel size is half of the foliage width in row crops. Setting *Tcanopy* to 25%-50% coldest pixel range is essential in sparse canopies. Choosing threshold levels between 25% to 50% is a matter of preference and standardization.

In digital aerial photography pixel size is the capacity limiting factor, as the swath width is the product of the number of image pixels by the pixel size. Efforts to extract crop temperatures from mixed pixels (Moran, T.R. Clarke et al. 1994) reached limited success so far. Thermal imagers are limited in pixel count, so economic efficiency and thermal survey accuracy must be optimized to achieve meaningful results.

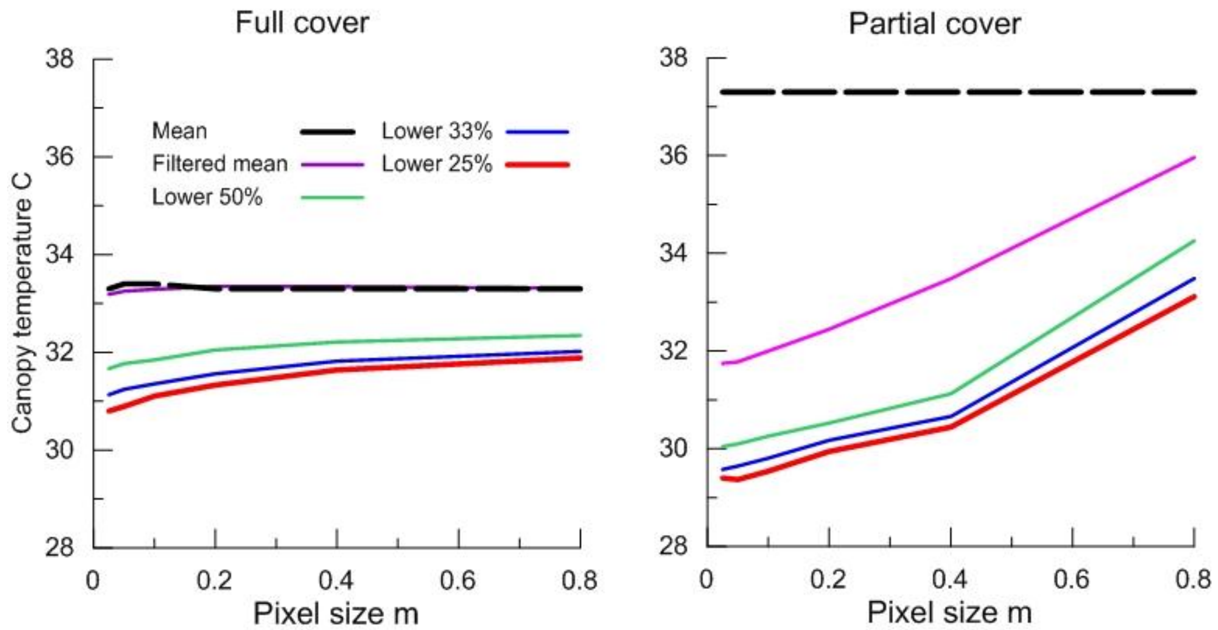

Figure 3. Mean canopy temperature of coldest 25%, 33%, 50% and 100% pixels of drip irrigated cotton after air temperature filtering, and without filtering, as related to pixel size: left-for full crop cover, right- for partial crop cover Ambient temperature was 2°C lower when partial cover images were acquired.

Image interpretation and spatial resolution.

Three principle methods are used for CWSI evaluation from a thermal image, in relation to ambient conditions:

- The "Big Leaf" energy balance paradigm, where the crop canopy is a virtual uniform flat surface receiving even radiation. In reality the surface is not uniform, so in practice the sunlit leaves are selected by superimposition of the thermal over the color image (Alchanatis, Cohen et al. 2006). To acquire "pure" canopy pixels without soil or shaded leaves temperature, the effective ground pixel size is limited to less than the sunlit leaves size. Color images with exact overlap of IR images must be taken simultaneously, quite a difficult task from aerial platforms. A ground based weather station is also necessary.

- The natural reference system, where well watered crop patches are maintained for *Tref* (Clawson, Jackson and Pinter 1989). A seemingly straightforward approach, which requires some efforts involved in patch maintenance. In experimental plots the contrast between irrigation treatments was apparent. At this point of time more development is needed to support practicality of this system in aerial surveys.

- Wet Artificial Reference Surface (WARS) method (Meron, Tsipris and Charitt 2003) (Meron, Tsipris et al. 2010a). Artificial reference surfaces are Styrofoam boards covered with white non-woven viscose cloth, floating in a water filled tray. The viscose cloth is kept wet by wicking water from the tray. A ground station (Figure 4.) measures ambient and WARS temperatures. CWSI is calculated by Eq. 1. using WARS temperatures as *Tref* and *Tair* +5 as *Tmax*.

The WARS method was lately proven as preferable over others tested in Israel (Alchanatis, Cohen et al. 2010) and became currently the de-facto standard in experimental and semi-commercial applications of aerial thermography for crop water stress evaluation there.

Figure 4. Ground station with Tair and WARS sensors.

Image acquisition.

The less expensive but also less accurate uncooled (bolometric) thermal imagers became popular over the more accurate and much more expensive cooled sensor (MCT and QWIP) types. Two main issues are problematic with bolometric imagers in aerial thermography: pixel smear and recalibration. Pixel smear is caused by the slow "shutter speed" (image registration time) of 0.007-0.008 sec of the sensor, over 40 m/sec of the slowest flight speed of a fixed wing aircraft, moving over the ground about 0.3 m with "open shutter". That means smearing the pixel over 0.3 m in the flight direction and blurring the image. Despite this limitation, we obtained meaningful results in aerial crop stress detection (Cohen, Alchanatis et al.; Alchanatis, Cohen et al. 2010) (Meron, Tsipris et al. 2010b). Uncooled radiometric imagers have ± 1°K best accuracy by design. They need periodic recalibration when the outer shell temperatures change. On the ground, in presence of a known reference, this is a tolerable problem. While in flight, recalibration may confuse and invalidate the results. Selection and operation of thermal imagers for aerial thermography must regard this issue and treat it properly. For commercial operations, where capital costs are recoverable, the more expensive cooled imagers would be preferable at comparable image detector size.

Geo-referencing and information presentation

Thermal images are small in size and to mosaic an exactly referenced ortho-thermogram (like an orthophoto) requires advanced photogrammetric methods, and specialized airborne equipment (Yalon 2011). Image frames are recorded by GPS location of the aircraft and the deviations of the aircraft position from azimuth and plane are corrected by inclinometers. Such ortho-thermograms enable to pinpoint various events and effects on the ground like clogged / broken emitters, or over / under watered trees in an orchard (Cohen, Alchanatis et al. 2011). Large area mapping of CWSI is done by post processing the thermogram.

Another approach is creating a less detailed, but still usable CWSI map of the field by simplified methods. Images are registered by the center point of the frame from the aircraft GPS location with azimuth correction only. The frame is broken up to smaller sub-frames, and their calculated CWSI values are assigned to each sub-frame's center points. Maps are generated by spatial interpolation of the CWSI points (Figure 5.).

While both methods provide visual presentation of the crop water status, a more practical presentation is needed for irrigation management purposes. Since irrigation management zones are defined by watering units, such as a center pivot segment, or similar, painting the zones in color scale from well watered to stressed status will assist decisions in a glance. In case leaf water potential (LWP) is more familiar to the

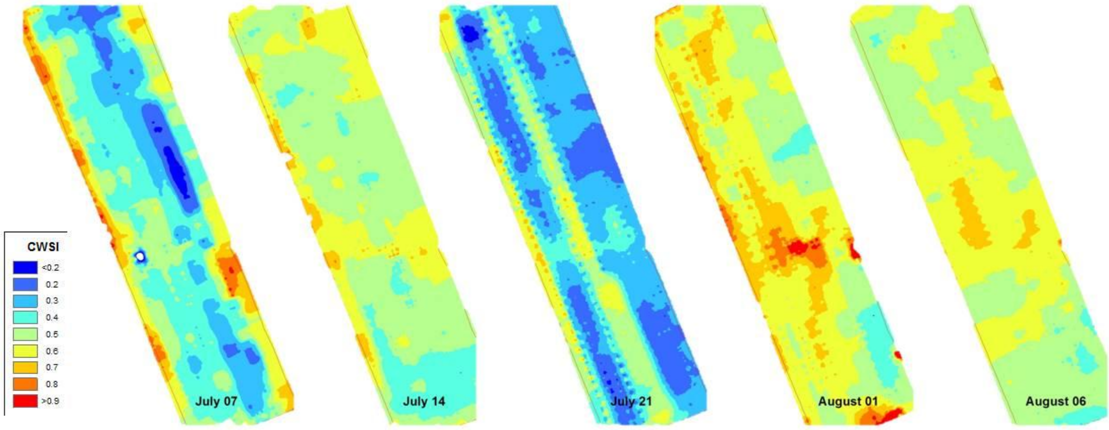

Figure 5. CWSI maps bi-weekly sequence of a drip irrigated cotton field generated by the simple interpolation method. (Unpublished data by Meron *et.al*. 2008.)

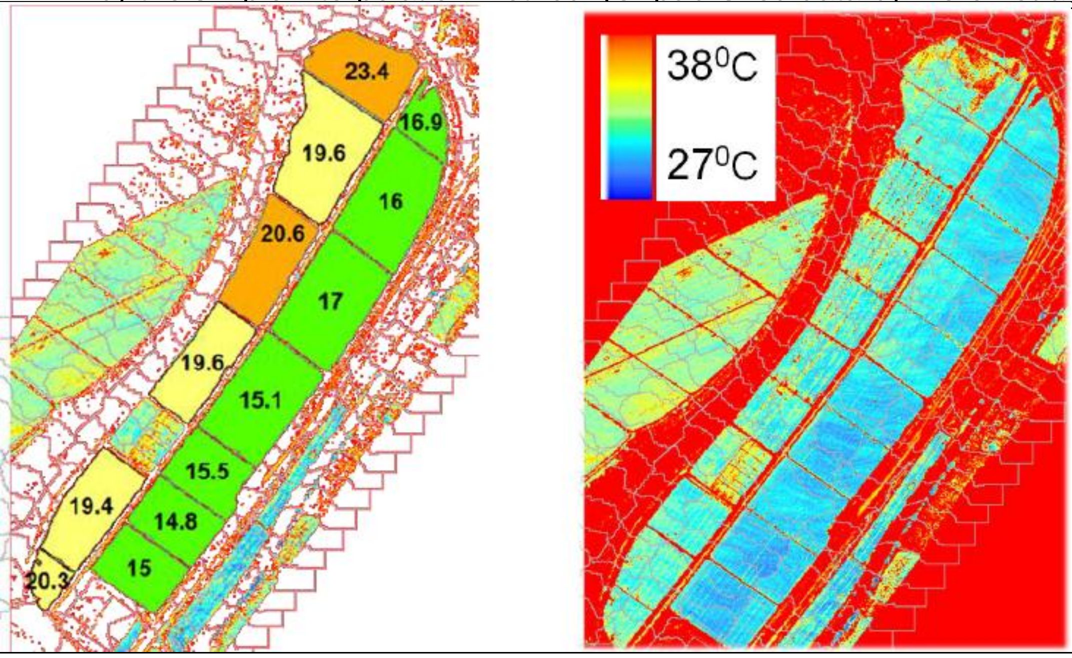

Figure 6. Ortho-thermogram of a cotton field (right) and calculated LWP assigned to irrigation management zones. From (Rosenberg, Cohen and Alchanatis 2011))

growers, CWSI may be converted to LWP according to (Cohen, Alchanatis et al. 2005) as shown in Figure 6.

Irrigation scheduling is based on water balance methods; replenishing water used up by the crop. Crop stress maps provide feedback on the water status of the crop to assess the efficiency of the water application and implement changes. Numeric presentation, assigned to management zones by tabulated or graphic statistics of CWSI (Figure 7.) may better fit irrigation scheduling routines than visuals and maps.

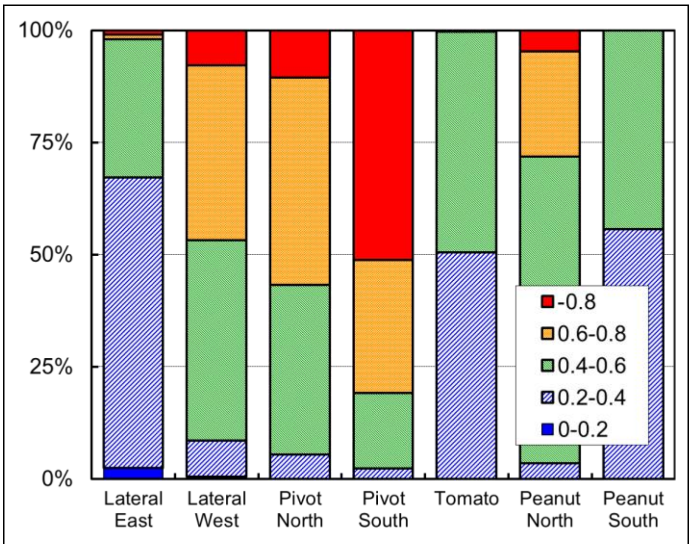

Figure 7. CWSI statistics by management zones (Meron et al 2010)

Conclusions

Crop water status mapping by high resolution thermography emerges as a viable tool for site specific irrigation scheduling. Separation of the canopy temperatures from soil and other hot backgrounds needs ample number of "pure", foliage only pixels in the frame, dictating finer spatial resolution than half of the row width in sparse crops. Canopy temperature can be extracted by thresholding the pixel histogram over and under ambient air temperature and averaging the colder fractions of the remaining histogram. Wet artificial reference surfaces or well watered crop patches can be used for cold reference in CWSI evaluation. For hot reference 5°C above ambient temperature is sufficient. While WARSs need ground based instrumentation, natural vegetation surfaces need only air temperature, though the natural method still needs further development. Image acquisition by uncooled thermal scanners in aerial applications must consider pixel smear caused by slow shutter speeds, and radiometric recalibration problems inherent to bolometric sensors. In digital aerial photography image size is a limiting factor, as the swath width is the product of the number of image pixels by the pixel size. Cooled thermal imagers are best suited to aerial thermography but are more expensive, and image sizes smaller. Ortho-thermograms of thermal aerials contain pin-pointed information on crop and irrigation status, but specialized aerial equipment and processing software are necessary. Simpler procedures are available for less detailed but still meaningful crop stress maps based on GPS tagging only.

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Estimating crop evapotranspiration through integrated surface and satellite observations

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Abstract. *. Knowledge of crop water requirements is paramount to efficient irrigation scheduling and optimum water use efficiency. However, accurate monitoring of such parameters can be challenging. Satellite imagery provides very extensive spatial measurements but remains very expensive and still need to be validated with surface observations at numerous locations. . Therefore, the goal of this study was to conduct surface observations of crop evapotranspiration data (ET) and crop coefficients (K_c) in an effort to compare them with satellite imagery at a later stage. Surface observations were developed through lysimeter studies where ET data were collected daily and measurements of crop ground cover were performed weekly to derive relationships between crop coefficients and fractional cover. The crop coefficients were obtained for processing tomatoes grown under sub-surface drip irrigation. This paper presents the preliminary results obtained from the first year study. Data indicated that the crop coefficients obtained at peak season were relatively higher than those generally reported for tomatoes. Results also showed good correlation between fractional cover and crop coefficients (r2 = 0.91).*

Keywords. Crop coefficient, water requirement, irrigation scheduling, lysimeter.

Introduction

Estimation of crop water requirements is critical to efficient irrigation scheduling and optimal management of water resources. A common method of irrigation scheduling involves estimation of crop water use by multiplying a weather-based estimate of reference evapotranspiration (ET_o) with a crop coefficient (K_c) specific to a particular crop. Coefficients have been compiled for numerous crops and are available through sources such as FAO56 (Allen et al., 1998), University of California's Basic Irrigation Scheduler, and California State University's WATERIGHT system. These crop coefficients varied during a growing season and are often reported as only four values representing main stages of growth. Therefore, development of a crop coefficient curve can sometimes be difficult, and in some cases, such as for many horticultural crops, data are not available. In addition, adjustment for local conditions can be very challenging because of the variety of cultural practices, climate, soil type, irrigation method, and planting density observed for individual fields.

Accurate development of K_c values is expensive and difficult to develop and most research has focused on crops with large acreage (wheat, corn and cotton in particular). Yet, vegetable and fruit production is important in states like California, and knowledge of K_c is paramount to efficient irrigation and water conservation. Satellite remote sensing offers an efficient way to observe crop development and generate critical crop parameters over large areas with reasonable spatial and temporal resolution. However, current satellite-based approaches are still difficult to run in real-time and need to be validated against surface observations of crop development and evapotranspiration. The most accurate approach to generate surface observations of crop evapotranspiration is through lysimeter studies. Lysimeters are heavy soil tanks positioned on a scale capable of measuring very small changes in weight due to soil evaporation and plant transpiration. These measurements taken in field crops to generate ET_c and in fields planted with a reference grass to obtain ET_o are then used to derive crop coefficients.

Previous lysimeter research has demonstrated a good relationship between crop coefficients and surface measurements of fractional ground cover, F_c (Bryla et al., 2010; Ayars et al., 2003; Williams & Ayars, 2005; Allen & Pereira, 2009). These relationships can then be applied to satellite observations obtained over large areas; however, they have only been developed for a limited number of cropping systems. Therefore, the overall goal of this study was to continue building these relationships for additional crops and testing the hypothesis that relationships between F_c and K_c are consistent across different canopy architectures. Specifically, the objectives of the research presented in this paper were to: 1) conduct lysimeter studies to determine crop coefficients for processing tomatoes grown under sub-surface drip irrigation, 2) develop relationship between crop coefficients and ground cover, and 3) determine the water use efficiency of the cropping system.

Materials and Methods

The study was conducted at the University of California Westside Research & Extension Center (WSREC), in Five Points, CA during the 2011 and 2012 growing seasons. The Center has two large weighing lysimeter facilities, each containing a 15-tonne soil tank (2 m x 2m x 2.25 m) positioned on a scale system capable of measuring small weight changes of less than 0.01 kg. The lysimeters are located in the center of two adjacent 1.7-ha (4.2 acre) fields. One lysimeter is planted with grass to measure the reference ET (ET_o). The second lysimeter, referred to as crop lysimeter, is planted with a particular crop of interest to obtain its actual ET.

This reported study focused on the development of ET and crop coefficient curves for processing tomatoes grown under drip irrigation. The tomato crop was transplanted both in the crop lysimeter and in the surrounding field on 60-inch beds. The tomatoes were planted 12 inches apart along the beds and were irrigated with a sub-surface drip irrigation system installed at 12 inches. The cultural practices and fertilizer applications followed the WSREC schedule.

The lysimeter was replenished each time an equivalent of 0.08" of crop ET had been withdrawn from the soil tank. The surrounding field was irrigated based on the ET data obtained from the crop lysimeter. Irrigation was applied daily. The parameters measured during the growing season included: daily ET_c, K_c, and water application; weekly ground cover and crop height; as well as yield and water use efficiency at the end of the growing seasons. Ground cover was obtained from a Tetracam infra-red camera. Water use efficiency was calculated as the ratio of crop yield over water applied.

Results and Discussion

The results presented in this paper include the preliminary data obtained from our first-year field study. Figure 1 shows the crop coefficient values obtained during the 2011 growing season. Due to operating problems that occurred with the grass lysimeter, the daily Kc values were calculated by dividing the crop evapotranspiration measured by the crop lysimeter with the reference evapotranspiration obtained from the California Irrigation and Management Information System station located a few hundred feet from the tomato field. The data indicated that the K_c curve followed the regular bell-shape. However, it showed that the average K_c values were: 1) higher than those reported by Allen et al. (1998) or Hanson and May (2006) at mid-season representing flowering and early fruit development stages (50 to 80 days after transplant), and 2) lower at the vegetative, earlier flowering, and ripening stages of the growing season.

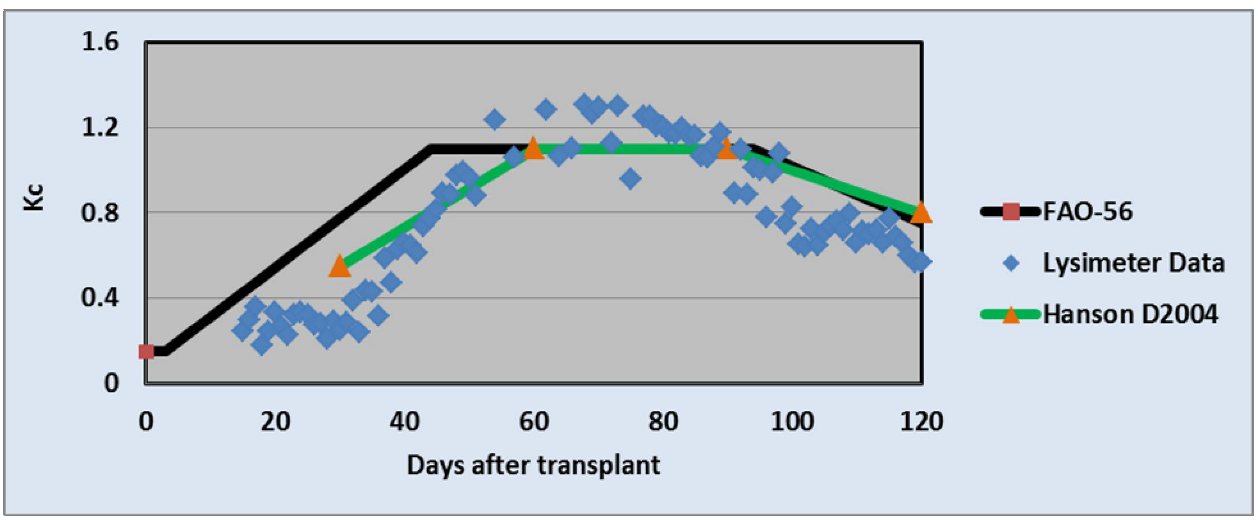

Figure 1. Crop coefficient curve developed during the 2011 growing season (preliminary data)

The relationship between fractional ground cover and crop coefficient is presented in Figure 2. Data showed a good correlation between the two parameters with a r^2 of 0.91. During most of the growing season, crop coefficient values increased with increasing fractional ground cover. At the end of the growing season, both parameters declined due to crop senescence. It was noteworthy that, for a period of about ten days, crop coefficient values started declining (80 days after transplant) while fractional ground cover still kept increasing until 90 days after transplant.

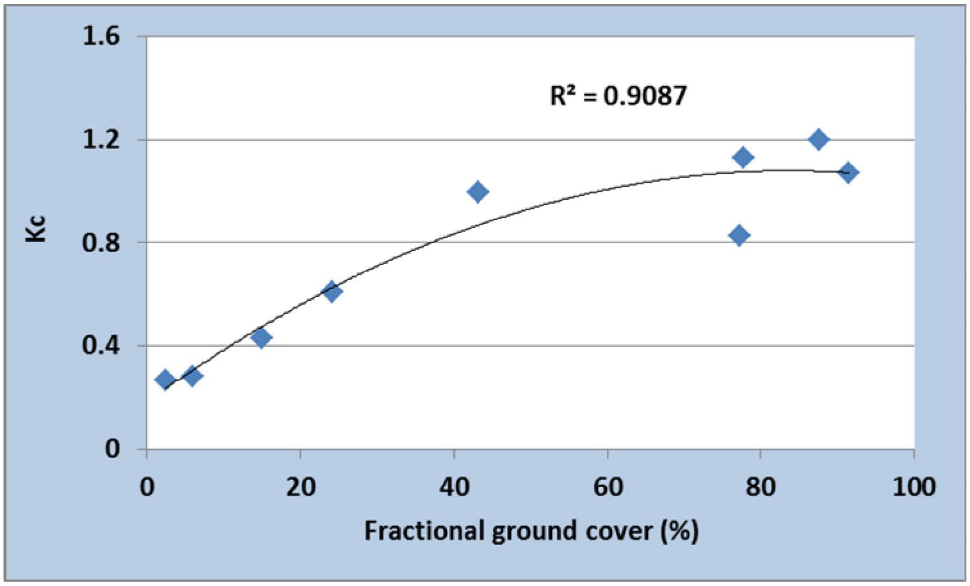

Figure 2. Crop coefficient as a function of fractional ground cover obtained during the 2011 growing season (preliminary data)

In this first season, tomato yield reached 39 tons per acre. Water use efficiency was 1.8 tons per acre per inch of water applied, which was consistent with data reported by Hanson and May (2006) for the region.

Conclusion

The preliminary findings summarized above represent those obtained from a first year field study conducted on processing tomatoes grown under subsurface drip irrigation. The goal of the overall research is to develop new crop coefficients or update crop coefficients for crops grown under different cultural practices than those reported in the literature. Ultimately, the aim is to develop relationships between fractional ground cover and crop coefficients for a variety of crop architecture and to compare these surface observations with satellite imagery that could then be used on a much larger scale.

The preliminary results of this first year field study showed that, compared to data reported in the literature, the crop coefficients for processing tomatoes grown under drip irrigation were lower at the vegetative, earlier flowering, and ripening stages of the growing season and greater at flowering and early fruit development. The data also showed a good relationship between fractional ground cover and crop coefficient. Additional lysimeter studies need to be conducted to confirm these results.

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Comparison of field level and regional actual ETc values developed from remote sensing and dual crop coefficient procedure

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Abstract. *Crop evapotranspiration (ETc) estimates are important for regional water planning as well as irrigation scheduling. Traditional ETc computations utilize published crop coefficients (basal) that are adjusted on a daily basis depending on soil water availability (i.e., dual crop coefficient method). Recent advancements include using remote sensing data such as LandSAT combined with a surface energy balance algorithm (METRIC), allowing crop evapotranspiration to be computed for each pixel throughout images taken during the season. There are limitations and advantages for both methods. Comparisons of soil water balance evapotranspiration values to METRIC values for two scenarios in different regions of California have been made. The comparisons show that when averaged either spatially or temporally, values estimated from the methods show a good relationship. However, there can be significant variability between the two methods when looking at instantaneous values (for a specific day that the LandSAT image was taken). The cause for this can be attributed to the inputs into the dual crop coefficient model. Both methods have advantages and disadvantages. If the user has good input information, both methods can provide accurate evapotranspiration estimates. Work is currently underway to leverage advantages from both methods by coupling them together.*

Keywords. *Evapotranspiration, irrigation scheduling, remote sensing, satellite, FAO 56, crop coefficients*

Background

The need for accurate evapotranspiration estimation cannot be understated. Evapotranspiration estimates are used for irrigation system design, irrigation scheduling, regional water management, and long-term water planning. Underestimating evapotranspiration can lead to poor yields because of insufficient irrigation or under-designed irrigation systems. Overestimating evapotranspiration will lead to excessive water losses (i.e., deep percolation) caused by over-application or unnecessary system cost when the irrigation system has been overdesigned.

Crop evapotranspiration (ETc) is the combination of evaporation from the plant and soil surfaces and transpiration of water from the plant tissue into the atmosphere. Transpiration and evaporation consist of vaporization of water from a liquid state. Since both processes occur simultaneously it is difficult to differentiate the two processes (Allen et al. 1998). In situations where there is healthy vegetative cover, transpiration will be the dominate process over the longer term (Burt et al. 2002). Obviously, in situations with minimal vegetation, evaporation from the soil will dominate.

ETc is driven by energy supply (solar radiation, temperature, etc.), vapor pressure gradient, wind, plant characteristics, cultivation practices, etc. (Allen et al. 1998). Direct field measurement of ETc is impossible on a large scale because of the wide variety of elements that influence ETc. The most effective tool, a weighing lysimeter, is utilized for research purposes only. Other technology used by researchers includes eddy covariance and Bowen Ratio sensors, which measure energy fluxes to estimate ETc.

Because of the difficulty of directly measuring evapotranspiration on a field or regional scale, a procedure has been used whereby ETc is estimated empirically using a reference crop evapotranspiration computed based on weather parameters and a crop coefficient that accounts for crop type. The reference evapotranspiration is computed based on a reference crop, typically either alfalfa or grass assuming the reference crop is well watered and there is no surface wetting (the reference evapotranspiration does not account for evaporation). In California, grass is the primary reference crop and grass reference evapotranspiration is denoted as ETo, where the subscript "o" indicates grass reference. ETc is then computed as:

$$ETc = ETo \times Kc \qquad \text{Eq. 1}$$

Where, Kc is the crop coefficient. Traditionally, Kc values were computed based on measured ETc and ETo as Kc = ETc/ETo. In most cases the Kc values are provided for three plant growth stages: initial, middle, and end. The length of each stage can be obtained from regional tables or computed using degree days (Allen et al. 1998). The ETc values are measured in research settings using weighing lysimeters or other methods. ETo values are computed by measuring relative humidity, incoming solar radiation, temperature, and wind speed at a properly sited, nearby weather station (Allen et al. 2005).

While the single crop coefficient method continues to be widely used, the transferability of Kc values is limited. These values are driven by assumed irrigation scheduling and cultural practices, which may differ in actual applications. Regional variability in weather conditions will also impact the transferability of Kc values (Allen et al. 1998).

In order to increase the transferability of the crop coefficient method, a more intensive approach of computing ETc was developed called the dual-crop coefficient method (Allen et al. 1998), which is based on a basal crop coefficient (Kcb). Kcb values have been derived in a similar fashion as Kc values, except that when the ETc is measured, care is taken so that there is minimal evaporation from the soil or plant surface and the crop being examined is well watered (i.e., no water stress). Therefore, multiplying Kcb and ETo results in a "potential" transpiration rate. Utilizing a daily soil water balance model, the cropping system is examined on a day-to-day basis with inputs including planting and harvest dates, growth stages, irrigation schedules, soil types, and cultural practices that may influence ETc.

The dual-crop coefficient method has been a significant improvement over the more traditional single crop coefficient approach. Basal crop coefficients are truly transferable as long as they were correctly developed. Most importantly, adjustments are made to the Kcb (and thus the ETc) to account for increased evaporation if the soil and plant are wet, or decreased transpiration if the soil moisture in the root zone is below a certain threshold (accounts for water stress). However, the dual crop coefficient method is more time consuming to implement compared to the single crop coefficient method, because the daily soil water balance must be examined. A dual crop coefficient daily soil water balance model requires very good input information, typically gathered through local grower interviews, to compute ETc accurately.

In the 1990's, a procedure was developed to use remote sensing data from satellite images (such as LandSAT) to directly compute actual evapotranspiration (Bastiaanssen et al. 2005). Using the thermal image available from special remote sensing technology, actual evapotranspiration can be estimated using a surface energy balance. While there are several methods available to compute actual evapotranspiration from remotely sensed data, the methodology behind METRIC (Mapping Evapotranspiration at High Resolution with Internal Calibration) has been designed for agricultural crop evapotranspiration estimation (Allen et al. 2007). The advantage of METRIC lies in the sensible heat flux computation, which is based on internal calibration. Unlike other energy balance methods, the internal calibration for METRIC is based on the selection of hot and cold pixels within agricultural fields. In addition, the interpolation of ETc between image dates is based on reference evapotranspiration (Gowda et al. 2008). Grass reference ETo is used for the Irrigation Training and Research Center (ITRC)'s modified version of METRIC, which is typically available throughout the western US on an hourly and daily basis.

There are distinct advantages and disadvantages to each of the methods described for estimating actual evapotranspiration. The single crop coefficient method is simple to implement but could result in inaccuracies due to actual weather conditions, limited transferability of published Kc values, variable cultural practices and irrigation scheduling, and different irrigation methods (flood, sprinkler, or drip/micro). The dual crop coefficient method is a significant improvement since the temporal resolution is improved with a daily time-step and corrections to ETc based on soil water content each day. However, this method continues to rely on inputs regarding planting and harvest dates, crop growth stages, and irrigation dates which will influence results. Both methods have limited spatial resolution since these are typically evaluated 1-dimensionally for an "average" condition.

The improved spatial resolution using METRIC with LandSAT provides a significant advantage over the other more traditional crop coefficient approaches. Influences such as crop stress, non-uniformity of vegetation, actual vegetative cover, etc. are accounted for in the images. Using LandSAT with thermal sharpening or aerial imagery, the resolution is high (≤30 meters) and a large region can be evaluated from a single image (LandSAT 5 image is approximately 170 kilometers x 170 kilometers). However, there is limited temporal resolution; the LandSAT satellites acquire images on a 16-day interval and if there is cloud cover, the available images are less frequent. The METRIC process requires approximately one man-day to process a single image when thermal sharpening is implemented, which is costly for long-term ETc evaluations.

The purpose of this study was to compare the results from METRIC and the more traditional dual-crop coefficient soil water balance model. Two scenarios were examined: the first was a large farming operation near Palmdale, CA (approximately 2,050 acres) and the second was applied to a large regional analysis of an irrigation district in the Central Valley of California (approximately 45,000 acres). For the farming operation, detailed information on planting/harvest dates, irrigation dates, volumes, and cultural practices are recorded daily, which makes it an excellent study area. The irrigation district evaluation utilized approximately 15 grower interviews to conduct the modeling. It is hypothesized that while both scenarios used the same methodology to compute ETc, the ETc will be more closely aligned between METRIC and the dual-crop coefficient method for the farming operation because of the quality of model input data. For both scenarios it is expected that the main differences between ETc values from the different methods will be found during the initial and developmental periods since these are the most difficult to estimate for the model.

Procedure

Two scenarios were examined to compare the dual-crop coefficient method with ITRC METRIC results: large farm operation and irrigation district. The comparison procedures for each scenario will be discussed in this section.

Farming Operation

Palmdale WRP agricultural site (Figure 1) contains 27 center pivots of varying sizes. The two crops grown throughout the 2,050-acre agricultural site are alfalfa and winter small grain mix (mixture of barley, oats, and wheat). A detailed description of the pivots and their operations can be found in Howes et al. (2007) and Gaudi et al. (2007). Data on cultural practices including volume of irrigation water applied, harvests, and planting have been collected on a daily basis for each center pivot throughout the study period. Weather data and center pivot flow are incorporated into the dual crop coefficient soil water balance model utilizing the FAO 56 methodology (Allen et al. 1998). This information is used to predict irrigation schedules and track water destinations.

Figure 1. Palmdale WRP Agricultural Site (AS)

Years 2007 and 2010 were selected for this evaluation because there was deliberate water stress in a number of center pivots during the spring and early summer of 2007. Since this farming operation relies on treated wastewater, it is difficult to match supply and ETc demands.

The goal of the operation is to utilize the treated effluent on a day-to-day basis. Therefore, the ag operation would plant crops in more pivots than there may be water for in the late spring and early summer and intentionally under-irrigate the pivots until the winter grains could be harvested. This would ensure sufficient area to use effluent during the winter when ETc is very low. During the summer when ETc is high the amount of acreage with a crop is reduced from 2,050 to approximately 900 acres (primarily alfalfa). In 2010, storage reservoirs became operational and there was no need to plant excess acreage. Therefore, starting in 2010, irrigations could be scheduled to meet ETc and distribution uniformity and minimize water stress.

A total of eleven LandSAT 5 images were examined in this study: seven from 2007 and four from 2010. Each image was processed using METRIC to compute instantaneous and daily ETc and the Kc. The image acquisition dates are shown in Table 1. Dates early in the year were selected since the winter grain crops were in the field and water stress (for 2007) was occurring towards late spring and early winter.

Table 1. LandSAT 5 Image acquisition dates for the Palmdale AS METRIC evaluation.

2007	2010
1/21/2007	3/18/2010
2/6/2007	4/19/2010
3/10/2007	5/5/2010
4/27/2007	6/22/2010
5/13/2007	
6/14/2007	
6/30/2007	

The ITRC METRIC procedure produces an image of instantaneous actual evapotranspiration at the time of image acquisition. By dividing this instantaneous ETc by the grass reference evapotranspiration (ETo) at the time of image acquisition, the crop coefficient (Kc) can be computed for each pixel. The Kc values within each Palmdale AS center pivot were extracted and compared to the predicted Kc values from the dual crop coefficient soil water balance model for that day.

Irrigation District

An evaluation of monthly crop evapotranspiration (ETc) values was conducted for a specific region along the west side of the San Joaquin Valley. ITRC had previously conducted long term water balance evaluations in this region and a specific irrigation district that has detailed crop information in GIS was selected for this ETc evaluation for a single year (2007). Primary crops in this region are alfalfa, cotton, corn, winter grains (for hay, silage, or grain), and tomatoes.

ETc values from three sources were compared:

1. DWR C2VSIM
2. Dual crop coefficient soil water balance (a.k.a. ITRC FAO 56 Model) values were previously developed as part of a water balance for the irrigation district. These ETc values have been corrected for bare spots and decreased vigor.
3. ITRC METRIC was utilized to estimate the ETc from the LandSAT 5 images taken in spring, summer, and fall, to compute actual ETc on the specific days the images were acquired.

The California Department of Water Resources (DWR) has developed a model called the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM). The monthly DWR C2VSIM ETc values for crops within the region of interest were extracted from the model and used in the comparison.

The daily soil water balance model was used to compute daily adjusted Kc and ETc based on typical cropping scenarios within the region. Grower interviews were conducted to provide inputs into the model including average planting and harvest dates, typical irrigation frequencies, irrigation methods, and cultural practices that could influence crop evapotranspiration. Digital NRCS soils maps were used to provide input information on soils in the region.

Three images were process using the ITRC modified METRIC procedure. The dates of these images were April 25, 2007, July 30, 2007, and October 5, 2007 to represent ETc from spring, summer, and fall. The instantaneous ETc was computed for each image and the Kc was computed using quality controlled and corrected ETo data from CIMIS Station #56 located near Los Banos, California.

The comparison was conducted on a monthly basis. The Kc computed on the image days was used to estimate the monthly ETc. Using the GIS field boundaries within the area of interest, the Kc values were averaged within each field boundary by crop type. For example, if there were 50 fields of cotton, the Kc's within the field boundaries identified by cotton were averaged into a single, average cotton Kc for that image date. Since the image dates were near the beginning or end of the months, that same Kc for each crop was used for two adjacent months:

- April 25, 2007 – (Kc used for April and May)
- July 30, 2007 – (Kc used for July and August)
- October 5, 2007 – (Kc used for September and October)

The estimated METRIC Kc values for the 6 months were multiplied by the monthly ETo to estimate the monthly ETc in this comparison.

Results

Farming Operation

Figures 2 and 3 show comparisons of crop coefficients (Kc) from the daily dual crop coefficient model and METRIC for 2007 and 2010, respectively. The center pivots were selected to show different crop types and scenarios. In Figure 2, Pivots 3, 4, and 5 are alfalfa hay with cutting during the summer approximately every 30 days. In this area seven to eight cuttings per year are typical. Pivot 6 has winter grain hay planted in late November 2006 and harvested in late April with sudan (a summer forage) planted in mid-June 2007. Sudan is harvested (cut and baled) approximately three times during the summer. Pivots 18 and 21 have winter grain hay that is harvested in early April and allowed to re-grow for a second harvest in early June. The second harvest of grain hay typically has a lower yield than the first.

The dual crop coefficient Kc (labeled "Kc") in the figures is the adjusted Kc accounting for (i) additional evaporation when the soil and plant are wet from rainfall/irrigation and (ii) crop stress when the soil moisture drops below a threshold level. The basal Kc is shown as a reference. When the soil and plant surfaces are wet the evaporation increases, as indicated by the "Kc" above the Basal Kc in the figures. When the soil moisture in the root zone drops below a threshold (typically 55-60% of available water has been depleted for these crops and soil types), the "Kc" drops below the Basal Kc curve. Water stress results in the plants having less ETc, as indicated by the Kc value dropping below the Basal Kc curve.

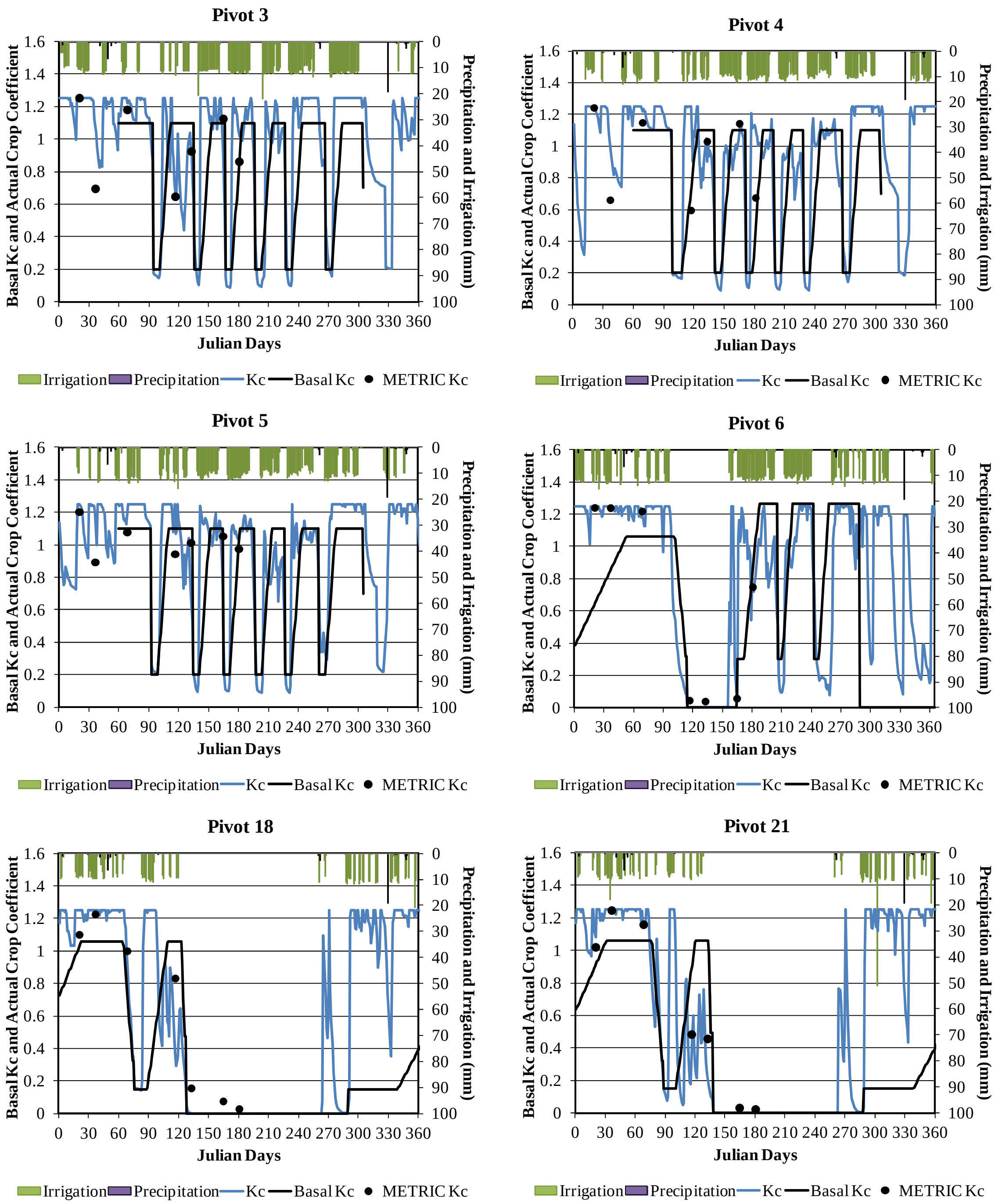


Figure 2. Comparison of daily adjusted Kc values (Kc) and METRIC Kc values for the image dates for select center pivots in 2007.

Figure 3 shows the comparison of the soil water balance Kc values and METRIC Kc values for several cropping scenarios. Alfalfa is shown in Pivots 2 and 11, two cuttings of winter grain hay in Pivots 14 and 17, single cut grain hay in Pivot 23, and single cut grain hay followed by a fall planting of new alfalfa in Pivot 5.

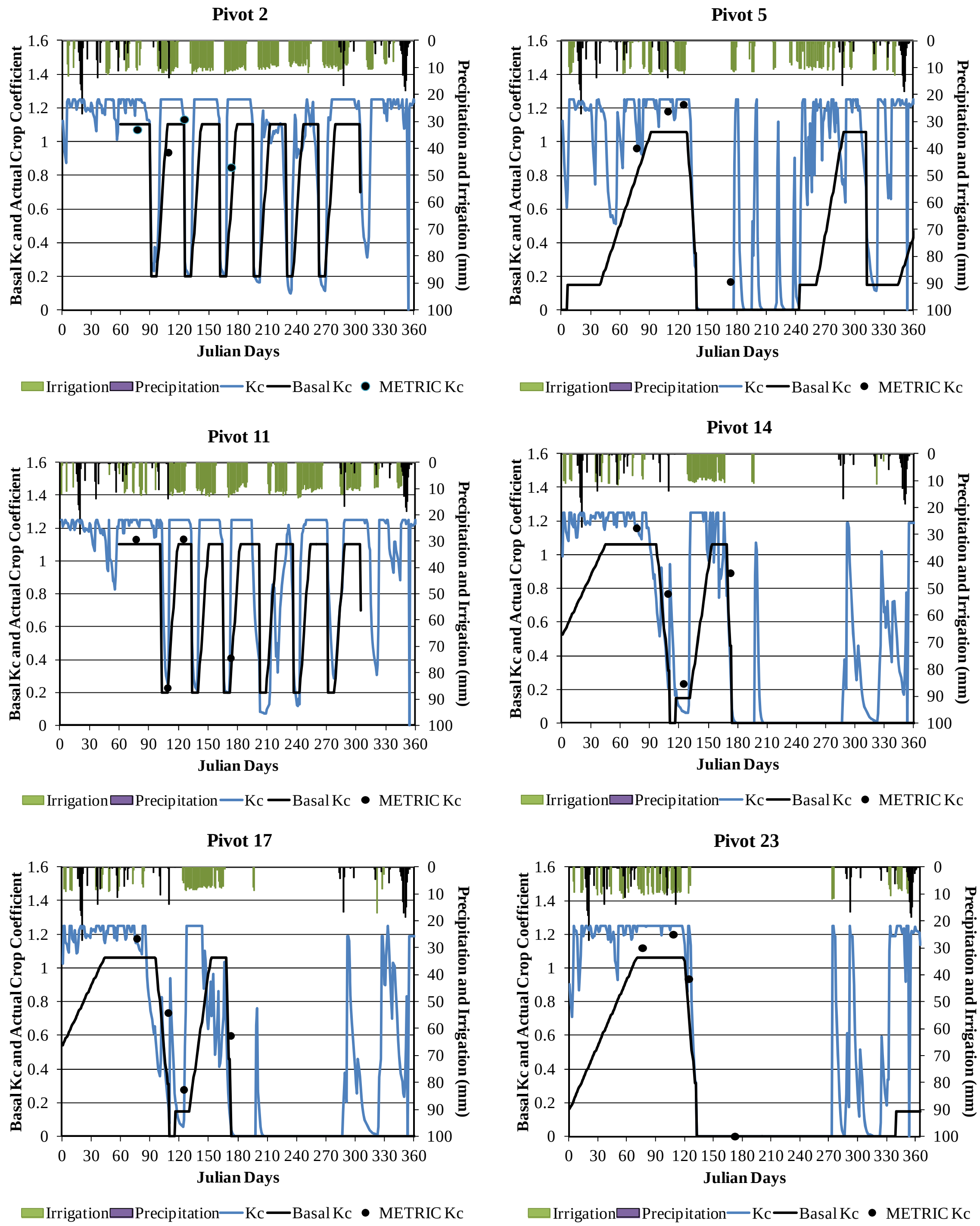
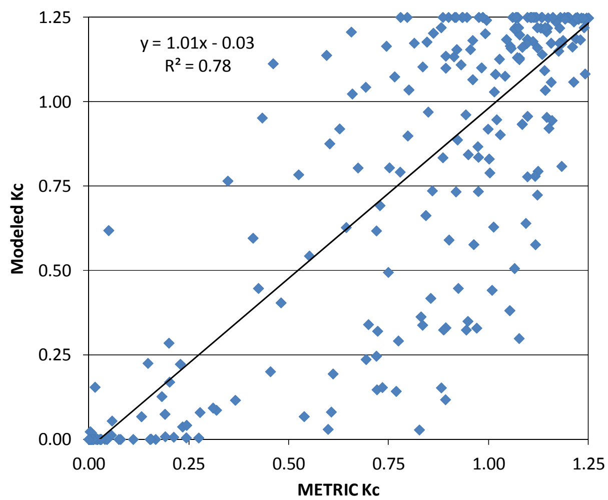


Figure 3. Comparison of daily adjusted Kc values (Kc) and METRIC Kc values for the image dates for select center pivots in 2010.

Figure 4 shows the comparison of modeled and METRIC Kc (field averaged) values for each field on each individual image date. The linear regression equation and r-squared value is shown. The METRIC Kc is can be considered the actual Kc and the figure indicates how well the modeled Kc's matched.

There is a significant amount of variability between the two Kc sources, more than might be expected when examining Figures 2 and 3. There are several issues that can contribute the variability. Through examination of some of the most significant outliers, one of the main issues is the way input information was recorded and entered into the dual crop coefficient model. For example, harvest dates are assumed in the model to have completely occurred by the date that was entered. However, in many cases the harvest may take multiple days or did not start until later in the afternoon. In this case the model shows a significantly lower Kc than METRIC. Similarly, the field is assumed to be irrigated entirely by the time the irrigation occurs. However, this is not always the case. Depending on pivot speed, only half or less of a pivot may be irrigated each day and therefore the METRIC Kc averaged over the entire pivot is lower than the model shows.



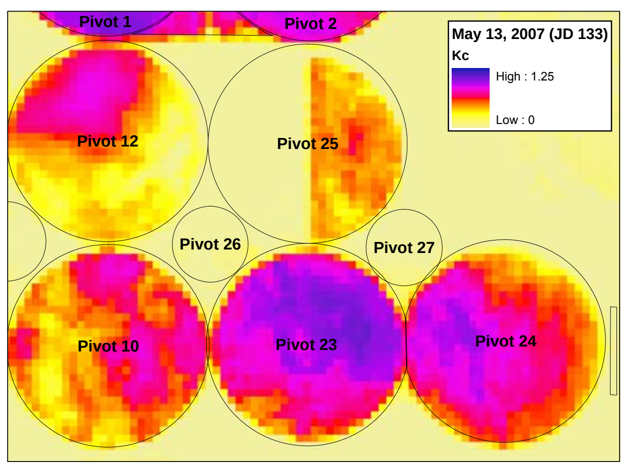


Figure 4. Comparison of METRIC and dual crop coefficient modeled Kc values (left). Example of variability in Kc values throughout evaluated fields (right).

Some examples of variability in actual field conditions are shown in the image on the right side of Figure 4. Pivots 12 and 25 were in transition at the time the image was acquired. The dual crop coefficient model assumes no transition and that practices occur immediately. Half of Pivot 25 had been harvested previously and Pivot 12 is being irrigated (after the alfalfa was harvested) at the time of image acquisition. The darker colors indicate higher Kc values.

In an attempt to minimize the daily variability, a general comparison of the modeled adjusted and METRIC Kc values was developed and is shown in Figure 5. Figure 5 (right) shows the monthly average Kc over all of the fields by month, compared for both methods during 2007. The METRIC Kc values were extracted from within the field boundaries and averaged over the entire farm. The month associated with a particular Kc value was assumed to be the month in which the image was acquired. Figure 5 (left) shows the monthly averaged Kc for each of the 27 fields. The METRIC Kc values were interpolated between image dates and a monthly average was developed.

For both figures, the dual crop coefficient model ETc was summed over the day of the month and divided by the monthly ETo to develop the monthly average Kc. From the comparison shown in Figure 5, the relationship significantly improved as would be expected when day-to-day variation is minimized. There is a slight tendency for the model to overestimate Kc compared to METRIC. That is not unexpected since METRIC accounts for actual field conditions such as bare spots, non-uniformity in planting, pest damage, decreased vegetative vigor, etc.

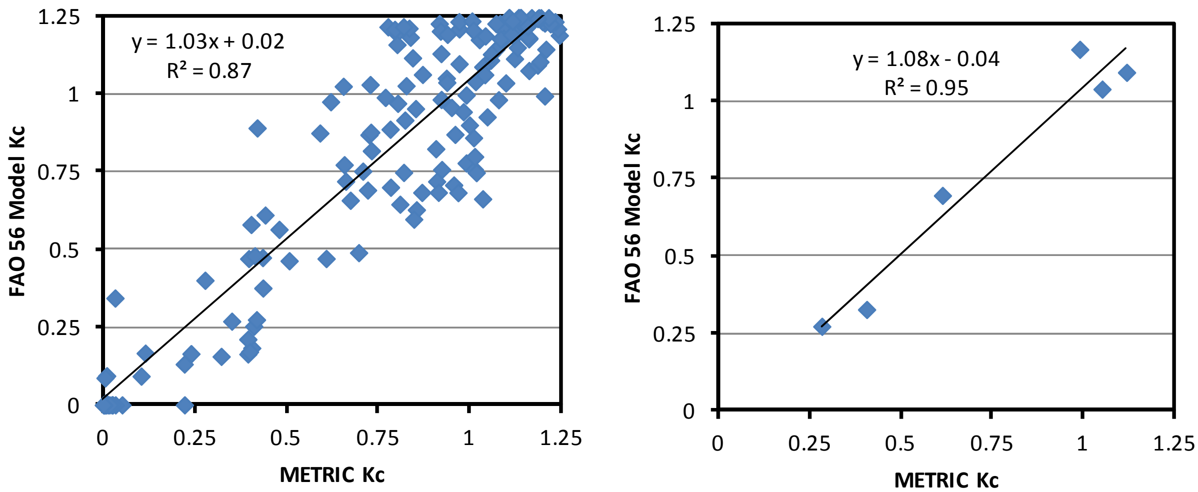


Figure 5. Monthly average Kc by field and month (left) and monthly Average Kc comparison with Kc values averaged over all of the fields (right).

A critical point that can be taken from this evaluation is that modeling results must be examined with care, especially when modeling small areas such as single fields. It is important that correct input data be incorporated into the model at any scale. However, small discrepancies in planting/harvest dates, irrigations application dates, etc. will tend to be averaged out over larger areas of investigation (i.e., more fields in the area of interest).

Irrigation District

The results shown in Figure 6 compare the monthly ETc depth from the three sources. The notations on the legend indicate the source: “DWR” is the C2VSIM values, “ITRC Model” is the FAO 56 based dual crop coefficient model, and “METRIC” is the ITRC modified METRIC remote sensing procedure. Four of the major crops in the region are compared: alfalfa, cotton, winter grain, and tomatoes.

While there were only three images processed for the METRIC evaluation, since the images were near the end or beginning of the month it was assumed that the Kc would be applicable for both months. Utilizing a single Kc for two consecutive months is not the most accurate procedure; however, for this evaluation it provides an interesting comparison. This is especially true for the spring Kc value since the Kc should be higher in May than in April for summer crops even though the image was taken at the end of April. Conversely, the Kc should decrease in May for winter grains (small grains) as the season progresses towards harvest.

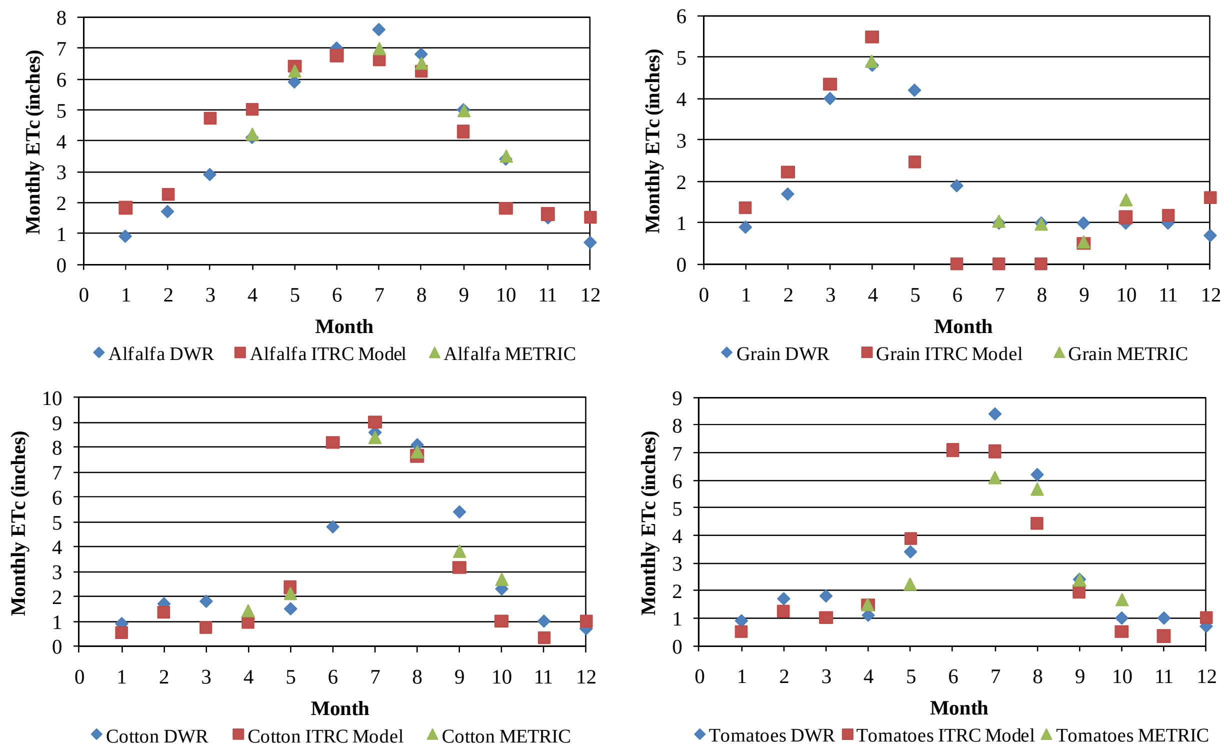


Figure 6. 2007 ETc Comparison between ITRC FAO 56 Modeled ETc, DWR C2VSIM ETc, and ITRC METRIC ETc for alfalfa, small grains, cotton, and tomatoes for the west side of the San Joaquin Valley.

The METRIC ETc values were averaged over multiple fields within the irrigation district. As with the farming operation scenario, this averaging eliminates much of the noise that would occur if only one field was examined. This is especially true for alfalfa, which has approximately 7 cuttings per year. For images taken after March and before November, a number of alfalfa fields will have been harvested. Averaging multiple fields accounts for alfalfa at different stages of development.

Overall the monthly ETc values from all methods seem to match well. One issue is related to summer ETc for grain. The ITRC model shows an ETc of zero while the others show approximately 1 inch of ETc per month (June and July). One likely reason that METRIC showed some ETc, even though the soil was supposedly bare, is that there were errors in the classification of the GIS field boundaries for the grain category. For example, if some of the fields had grain that was followed by summer corn or sudan, those fields would show some ETc but not from the winter grain. That would lead to some fields showing high ETc but once all fields classified as “grain” were averaged, the ETc would be only 1 inch per month. The ITRC model assumed grain hay that was harvested in early May and not allowed to re-grow and therefore once the soil moisture was depleted there was no longer ETc.

Conclusion

There has been a significant amount of research on ETc estimation over the past century. Recent developments in computing actual ETc using remote sensing have improved the accuracy and spatial resolution. However, the procedures are time consuming, images are limited temporally, and the process requires oversight by someone with detailed knowledge of cropping systems, irrigation, and plant water use. It is also difficult to forecast future needs using historical images without some type of forecasting algorithm (ITRC has a forecasting algorithm in the dual crop coefficient model to estimate future irrigation requirements).

Computer modeling using a daily soil water balance is less time consuming but the modeler must have knowledge of the systems and plant water use as well as detailed input information for the model. This procedure has spatial limitations since it is unreasonable to simulate every possible cropping scenario within a region or even a field that has spatial variability.

The results from the farming operation study are important for understanding some of the limitations from both methods. The METRIC has temporal limitation since the images are available at most every 16 days and the ETc is really a snapshot during the day. If a field is being irrigated or harvested the Kc values could be skewed between image acquisition dates.

The model also has limitations since vegetative non-uniformity is difficult to take into account. In addition, accurate input information is required for modeling to be successful. One advantage of the daily model is that if a harvest or planting date is off by several days, the overall error is not very significant on a monthly or annual basis as indicated in the comparison of average monthly values.

Looking at spatially and temporally averaged ETc and Kc values, the METRIC and dual crop coefficient modeled outputs (both with very good input information) match up well even though the daily comparison showed significant variability. Again, this variability is due to cultural practices and spatial variability that were not accounted for in the modeling.

From the results of this study several conclusions can be drawn:

- For a day-to-day irrigation schedule, using weather-based dual crop coefficient modeling is advantageous since it will most likely not underestimate the amount off irrigation required.
- The dual crop coefficient modeling should be checked periodically using independent verification such as METRIC. This will also provide the user with the spatial variability in ETc throughout each field, which can provide important management information.
- For regional water assessments METRIC provides accurate ETc estimates regardless of the accuracy of crop type acreage accounting. There is really no way to differentiate the ETc from irrigation water or precipitation, however, and timeframes over 3-4 years can be cost prohibitive.
- For long-term regional water use assessments, combining METRIC with the dual crop coefficient modeling has been successfully implemented by ITRC. METRIC provides a check on planting and harvest dates, overall vegetative health, and other important inputs that are used for modeling. The model provides the ability to cost-effectively examine long-term ETc. In addition, the ITRC dual crop coefficient model can separate the ETc from irrigation water and precipitation, which is needed for proper irrigation efficiency computations.

Future work that will benefit this evaluation is use METRIC to compute actual ET for LandSAT images during the remainder of 2007 and 2010. This will allow for more accurate interpolation of ETc between image dates and provide an annual ETc estimate on a field by field basis which can be compared against the dual crop coefficient model. Coupling the two methods has been successfully implemented on a recent project (not shown) however more work is necessary to quantify the accuracy improvements.

Acknowledgements

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Material Choices for Mechanized Effluent Irrigation Systems

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Introduction

The challenge of feeding, clothing and fueling the needs of the global population is one that continues to escalate in complexity. According to the latest UN projections, world population will rise from around 7 billion today to 9.1 billion in 2050.[1] According to the World Health Organization, today, water scarcity affects one in three people on every continent of the globe.[2] In the face of these and other trends, some groups are projecting a need to fully double agricultural outputs between now and 2050.[3] The role of irrigated agriculture in surmounting this challenge is clearly illustrated by the fact that while less than 20% of global cropland is irrigated, this land produces 40% of total agricultural output.[4] By using irrigation to facilitate plant vigor and productivity, yields can be as much as 230% higher than non-irrigated land.[5] Water is finite in nature and competition for access to water in sufficient quantity and quality for agriculture is escalating. It is important to maximize water productivity and limit impacts on water quality. This requires the reinsertion of some basic understanding in the way we use water on the farm and in other places. Instead of treating water in a linear fashion, where water enters one end of the farm and exits on the other, there is a need to get back to the basic understanding that water is in fact cyclical in nature. By deploying water reuse strategies with the goal of limiting physical, chemical and biological load on return flows, net inputs can be reduced and off-farm impacts can be lessened or negated entirely.

The modern farm is in fact, poised to become a much more prolific tool in the realm of water treatment as many constituents found in various effluent sources provide nutrition or other benefits to vegetation. Sources of reuse or reclaimed water are quite diverse. Depending upon the types of on-farm activities, as well as associated uses in the general vicinity of the operation, a wide variety of sources may be available. With nearly every primary use of water, there exists a potential for safe reuse. With some creativity and applied science, sources may be derived from but not limited to rain/stormwater, animal feeding operations, food processing, cooling/chilling, condensate recovery, industrial processes and/or municipal effluent. Of course, each of these sources require analysis of the various physical, chemical and biological properties to determine how best to safely apply such resources and to ascertain if some form of treatment may be necessary prior to such reuse. Such analysis is also important to determine the nutrient content of the reuse water as the target crop will benefit from and process constituents such as nitrogen, limiting the need for additional application of nitrogen while reducing offsite loading as well.

Once sources have been determined and qualified for reuse, the challenge turns to the application method and supporting infrastructure. While a variety of techniques and hardware are available, mechanized irrigation systems possess many desirable characteristics for such reuse applications. With appropriate planning, equipment selection and management,

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[1] Food and Agriculture Organization of the United Nations. http://www.fao.org.

[2] World Health Organization. http://www.who.int

[3] Global Harvest Initiative. http://www.globalharvestinitiative.org.

[4] NumbersUSA.com, "U.S. Population Growth is a Key Factor in Paving the World's Breadbasket" (2009).

[5] Michael F. Dowgert, PhD, "In Defense of Irrigated Agriculture" (presentation, Irrigation Show Technical Conference, San Antonio, Texas, Dec. 2-4, 2009).

mechanized irrigation can become an effective effluent treatment strategy while providing necessary, supplemental irrigation.

Operation & Maintenance

Mechanized irrigation systems utilize a moving array of structural components and sprinklers to convey and apply water over larger areas. This frequently means fewer components are necessary per field as compared to the various types of fixed or permanent arrays of irrigation components. Fewer components mean fewer service points and less time required for monitoring and oversight.

In reuse systems, source water often contains some suspended material. Mechanized systems can be designed with higher tolerances to such material by increasing nozzle opening size and sprinkler styles to suit the desired characteristics. Such material can also be centrally filtered to facilitate passage and application through the system. Filtration systems can even be designed to facilitate automatic cleaning/flushing.

The majority of the key components of a mechanized irrigation system are highly visible and accessible. This simplifies the tasks of verifying proper operation, diagnosing any problems and allowing access for any repairs or maintenance. For example, many sources of reuse water contain suspended solids which can potentially create the need for cleaning sprinkler/nozzle assemblies, which can be easily diagnosed and serviced because of such visibility and access.

With mechanized systems, underground obstacles are minimized and/or consolidated as mechanized systems only require source water and/or an energy source such as electric power. This minimizes interference with land use, harvesting, tillage, planting and other various operations that may be encountered with various other types of fixed arrays of irrigation components.

The adaptability of pivots to various crops, conditions and source water is also advantageous. Sprinkler packages and application height can be adjusted or changed with relative ease to comply with water quality, crop need, climatic conditions and soil type.

Application and Uniformity

A wide variety of sprinkler packages and application methods are available for pivots. Liquid can be applied at grade level using drag hoses, above vegetation with a variety of spray and rotary type sprinklers or with high-volume arrays of large scale impact type sprinklers. In any case, mechanized systems can be designed to apply water in a highly uniform fashion and periodically analyzed to verify ongoing performance and uniformity.[6] Additionally, some development toward varying application rates is gaining in popularity and recognition as systems can be engineered to vary application rates based upon field/crop specific data by varying machine speed and cycling sprinklers or groups of sprinklers on and off systematically.[7] This sort of precision application can become a critical factor in reuse applications which are

[6] Harrison and Perry. 2010. "Evaluating and Interpreting Application Uniformity of Center Pivot Irrigation Systems"

[7] Perry and Milton. 2007. "Variable-Rate Irrigation: Concept to Commercialization"

part of a nutrient management system[8], designed to utilize vegetation to process nitrogen or other nutrients and minimize migration of such nutrients into undesirable locations.

Durability and Chemical Resistance

Mechanized systems irrigation systems are constructed of a variety of materials suitable for the conveyance of a broad variety of reuse water. Key structural elements and distribution components can be constructed of a broad array of metals, alloys, plastics and other composites. Water from various sources may contain a broad array of constituents[9] that influence material selection as many such constituents can cause accelerated corrosion. Corrosion can be mitigated with proper regard for this interaction. Manufacturers (listed elsewhere) now produce mechanized systems irrigation systems and sprinklers from a wide variety of plastics and metals. Structural elements are readily available in galvanized steel, aluminum, chromium nickel, stainless steel or polyethylene lined galvanized steel. Manufacturers often provide recommendations for the best system longevity once there is an understanding of the constituents contained in the source water.

While it is desirable to choose system materials offering the best resistance to any corrosion potential caused by source water, system life can be substantially increased by flushing components with fresh water after each use or at regular intervals to remove residues and deposits that may be caused by reuse water. In areas with limited rainfall or where deposits/residues accumulate on external system surfaces, longevity of structure can be increased by periodic cleaning or rinsing.

Conclusion

This paper is developed for the sole purpose of supporting the adoption of mechanized irrigation technology for reuse applications and in no way is intended to endorse any specific product or supplier, yet it is important to note where to look for additional options and information. At one time, several dozen manufacturers were involved in the production of mechanized irrigation systems. Over time, the U.S. market has distilled down to five major manufacturers:

-Lindsay Manufacturing (Zimmatic), www.lindsaymanufacturing.com

-Pierce Corporation, www.piercecorporation.com.

-Reinke Manufacturing, www.reinke.com

-T-L Irrigation, www.tlirr.com

-Valmont Industries (Valley), www.valmont.com

Similarly, sprinkler manufacturers have undergone a market evolution where two companies fulfill the majority of current marketplace demand:

-Nelson Irrigation Corporation, www.nelsonirrigation.com

8 Howes, Gaudi, Ton. 2007. "Effluent Nitrogen Management for Agricultural Re-Use Applications"

9 Hoffman, et al. 1982. "Design and Operation of Farm Irrigation Systems", Chap. 20, Table 20.1

-Senninger Irrigation, www.senninger.com

Agricultural producers are already utilizing many alternative sources of water for irrigation. Many times, the producer's primary goal is to dispose of water that has embedded elements from associated farming operations such as manure management or food processing. Agricultural stakeholders must continue to develop practices and awareness as to how waste management operations and various primary water uses can be converted into safe, beneficial reuses. Trends in population and projected demand for agricultural products will likely lead to higher water costs and increased competition for necessary water. Cultivating alternative irrigation water sources from both on and off the farm is a desirable practice and mechanized systems possess many suitable characteristics which not only accommodate the need, but allow significant flexibility that will assist the producer with achieving his/her environmental, social and economic goals for the future.

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Simplifying Micro-Irrigation System Design with AquaFlow 3.2 Design Assist Software

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***Abstract*.** Micro-Irrigation system design can be an iterative, time-consuming process since multiple input variables must be evaluated in terms of the resulting irrigation conditions, as well as the flushing conditions. AquaFlow 3.2, a new micro-irrigation design program, uses a dynamic “dashboard” approach that allows the designer to easily and instantly view, on one screen, the results of all input choices including product selection, inlet pressure, slope, sub-main size and location, flushing velocity, and block dimensions. As the designer makes choices, both calculated and graphed output parameters are instantly updated along with a unique color-coded block map that visually depicts system uniformity. With this new software tool, designers can also compare the results of using one particular model of tape or dripline against another, and multiple slopes may be entered for the lateral, sub-main and mainline, as well. In this presentation, AquaFlow 3.2 will first be introduced and then demonstrated live.

Keywords. *Drip Irrigation, Micro-Irrigation, SDI, Irrigation Design, Emission Uniformity, Flushing.*

Introduction

Micro-Irrigation, also commonly called drip irrigation, is the fastest growing irrigation technology in the Unites States. It was commercially introduced over four decades ago, and its usage has since spread to 3.5 million acres of diversified farmland throughout the US as of 2008 (USDA, 2008). Farmers adopt drip irrigation because their crops respond well to the spoon feeding of water and nutrients directly to the crop’s rootzone, and because valuable resources are conserved and/or optimized. These benefits improve farm income and reduce farm costs enough to pay for the investment quickly. In addition, runoff, wind drift and deep percolation of irrigation water is minimized, and access to the field is improved compared to other irrigation methods. Figure 1 graphically describes these benefits (Corcos, 2012).

Drip irrigation differs from gravity and sprinkler irrigation in a number of ways. A drip system consists of a network of plastic pipes and emission devices that deliver pressurized water directly to the soil at a low pressure and low flow rate. It is typically operated at frequent intervals, and the duration of operation may be adjusted to accomplish numerous changing objectives. Source water is filtered to prevent clogging of drip system emission devices, and chemical injection systems are used to apply fertilizers, crop protection materials and drip system maintenance chemicals. (Stetson, 2011). Figure 2 shows a Typical Drip System Layout for field crops (corn), row/vegetable crops (lettuce), vineyards (grape vines) and orchards (almond trees). (Toro, 2012)

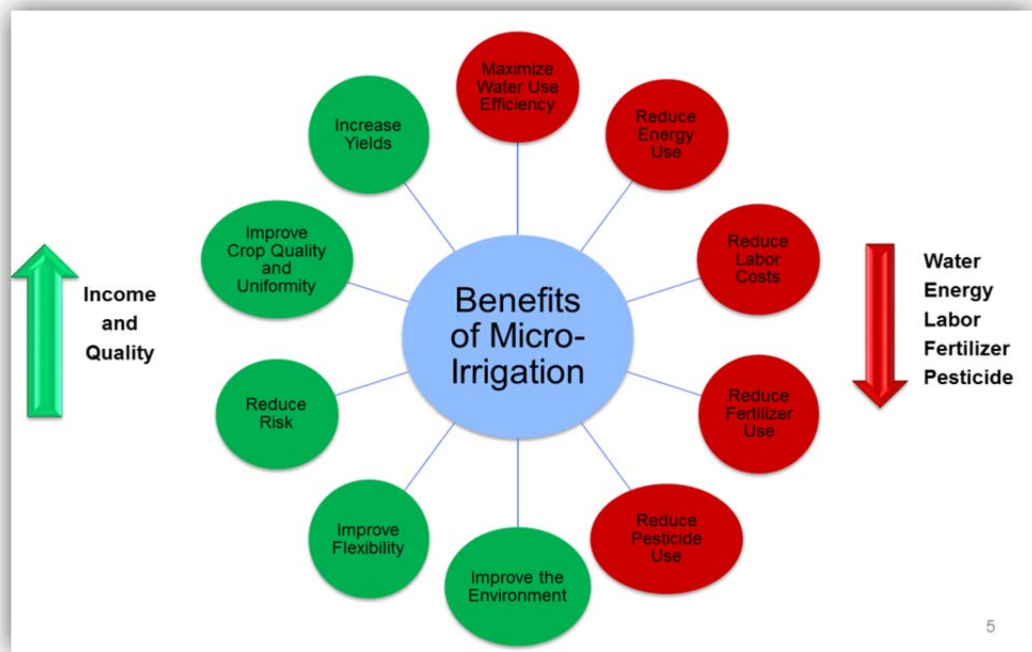


Figure 1 - Benefits of Micro-Irrigation

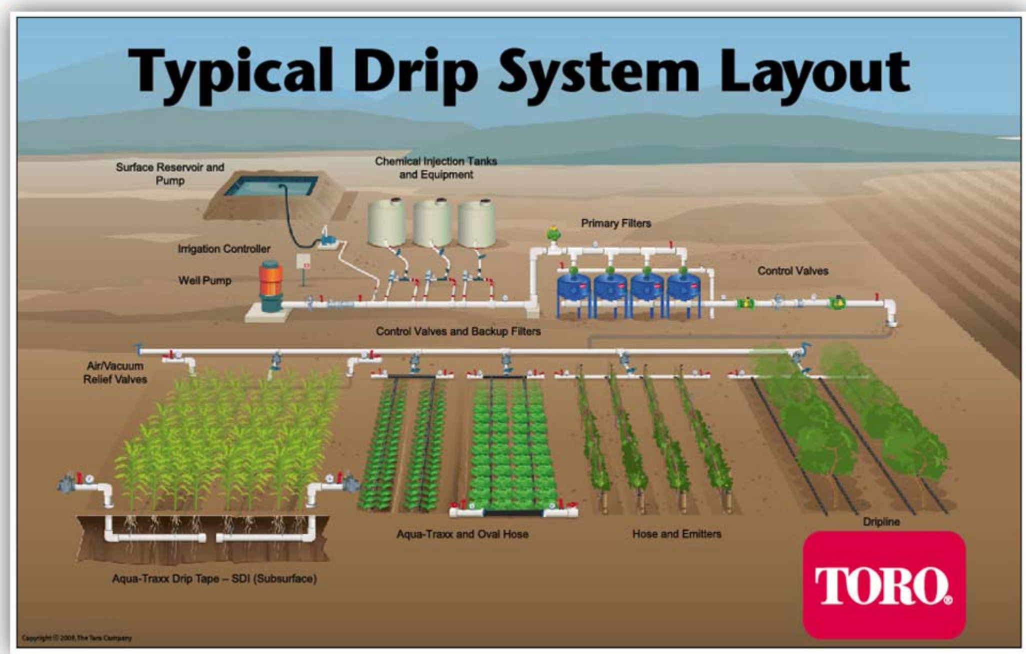


Figure 2 - Typical Drip System Layout

Although all irrigation system types share some basic hydraulic principles and equipment such as pumps and delivery pipe, there are also differences that require specialized knowledge for design, installation, operation and maintenance of the systems. The primary job of a drip irrigation system designer is to choose the right types and sizes of system components to ensure that the system applies water uniformly to each plant, and so that the system may be flushed and maintained to ensure a long life. Prior to the availability of software, designers manually calculated friction loss and flow uniformity, or used charts and nomographs developed for this specific purpose. With the introduction of consumer computers, early versions of drip irrigation design software automated many of these tasks and allowed a higher level of accuracy to be achieved.

Today, drip irrigation design has never been easier or more accurate. AquaFlow 3.2 takes advantage of recent advancements in computer processing, programming techniques and display screen technology to optimize drip irrigation design. Designers can now evaluate more selection options more quickly and more accurately than ever before, thus improving the decision making process in selecting drip irrigation system components. This will result in better, more cost effective drip irrigation system performance, and thus improved return on the investment for the farmer.

AquaFlow 3.2 Design Assist Software Platform

AquaFlow 3.2 is a new software program available for free download from Toro's website at toro.com upon approved registration. It currently supports Toro's Aqua-Traxx and Aqua-Traxx PC premium drip tape, as well as BlueLine PC and BlueLine Classic dripline. AquaFlow 3.0 features a unique "dashboard" which allows users the ability to view changes to inputs instantaneously, on one screen. This is in contrast to other design programs which require toggling between screens to view this type of information. The following is a full list of AquaFlow 3.2 features:

- A unique "dashboard" format that instantly shows the following as a result of Inputs:
  - Lateral and Sub-Main Irrigation Outputs
  - Lateral and Sub-Main Flushing Outputs
  - Tiled graphs of system parameters that may be viewed simultaneously or individually
  - A color-coded Uniformity Map that depicts block uniformity
- Easy comparison of two different lateral selections
- Pull-down menus for easy viewing
- Multiple slopes in the lateral, sub-main and mainline programs
- Choice of multiple sub-main and mainline pipe types and sizes
- Customizable reports that may be saved in multiple formats
- English and Spanish language support
- Standard English or Metric Units

The “Dashboard”

The dashboard is organized into eight areas:

1. Pull Down Menus
2. Toolbar Icons
3. Block Design Description and Project Selection
4. Lateral: Input and Output
5. Sub-Main: Input and Output
6. Flushing: Input and Output according to a) Inlet Pressure and b) Flushing Velocity
7. Color-coded Uniformity Map illustrating percent flow deviation from average
8. Tiled graphs showing pressure, flow, elevation and velocity information vs. lateral or sub-main length of run.

Figure 3 is a screen capture of the dashboard that appears right after launching the program from the desktop icon, and after selecting the Chart Tile function.

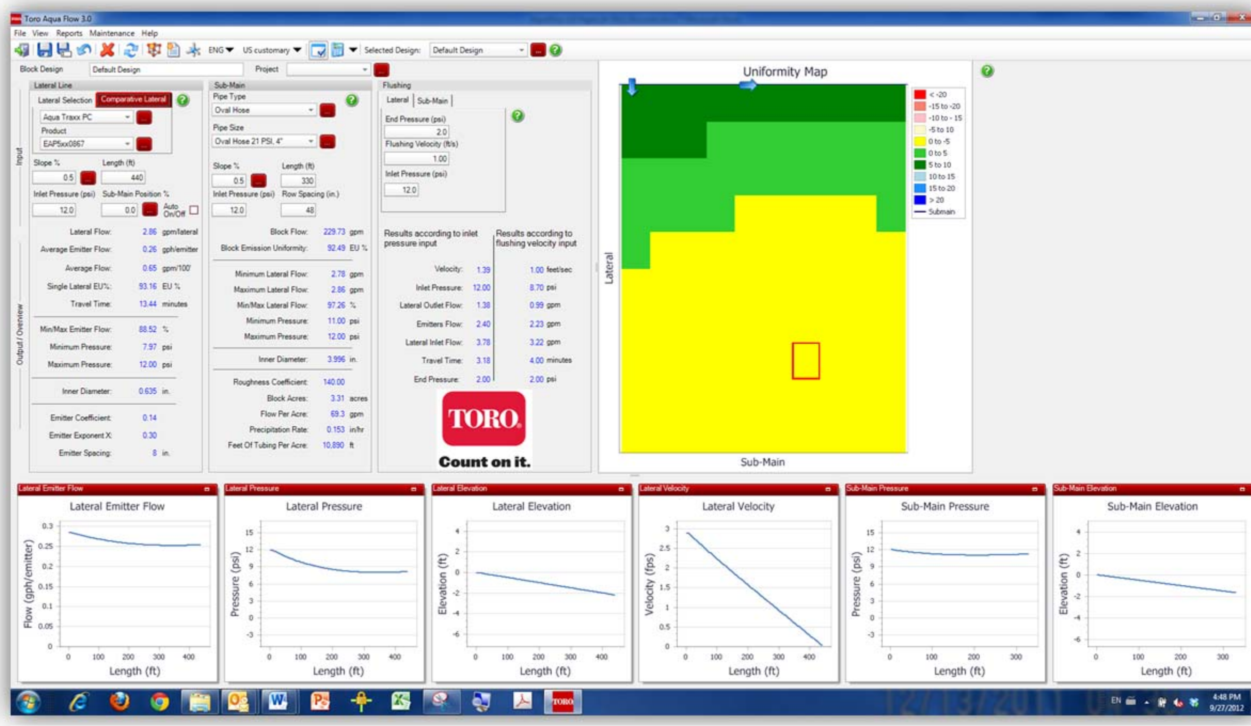


Figure 3 - AquaFlow 3.2 Dashboard

The Lateral, Sub-Main, and Flushing areas of the dashboard require input from the designer. Once data is entered, all output data, including the Uniformity Map and the Tiled Graphs, are instantly updated with the results of the new calculations. An overview of what the designer may view and use on the dashboard follows.

- Lateral:
  - Input: Product Model, Slopes, Length, Inlet Pressure, Sub-Main Position
  - Output: Lateral flow, Emitter Flow, Average Flow, Single Lateral Emission Uniformity, Travel Time, Min/Max Emitter Flow, Minimum Pressure, Maximum Pressure, Inner Diameter, Emitter Coefficient, Emitter Exponent X, Emitter Spacing.
- Sub-Main:
  - Input: Pipe Type, Pipe Size(s), Slope(s), Length, Inlet Pressure, Row Spacing.
  - Output: Block Flow, Block Emission Uniformity, Minimum Lateral Flow, Maximum Lateral Flow, Min/Max Lateral Flow, Minimum Pressure , Maximum Pressure, Inner Diameter, Roughness Coefficient, Block Size, Precipitation Rate, Length of Tubing and Flow.
- Flushing: Lateral and Sub-Main
  - Input: End Pressure, Flushing Velocity, Inlet Pressure
  - Output: Velocity, Inlet Pressure, Lateral Outlet Flow, Emitter Flow, Travel Time, End Pressure

Figure 4 shows the Lateral, Sub-Main, and Flushing areas of the Dashboard in more detail:

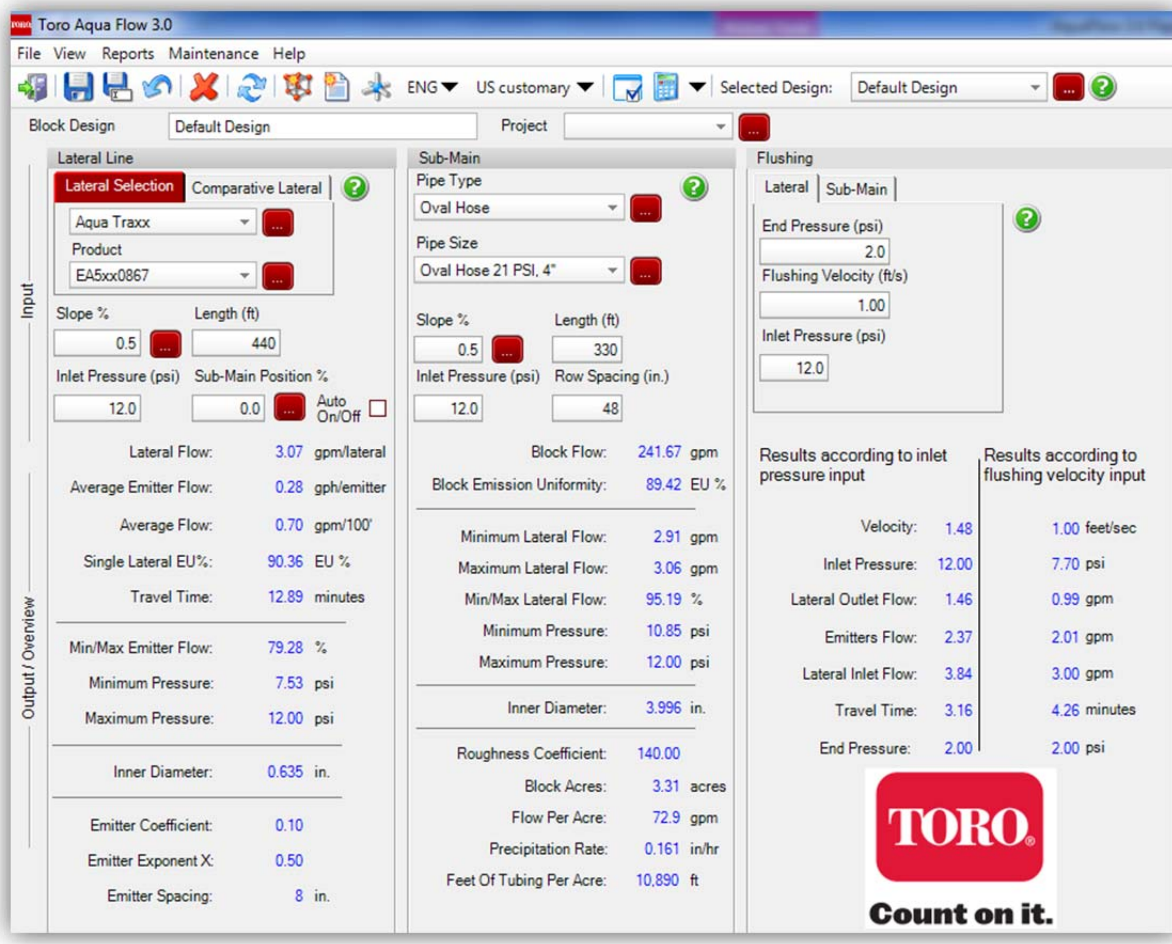


Figure 4 - Lateral, Sub-Main, and Flushing areas of the dashboard.

Another key feature of the dashboard is the Chart Tile area, which plots six drip system operating parameters vs. length of run. The default view minimizes the Chart Tiles at the bottom of the dashboard as shown in Figure 5:

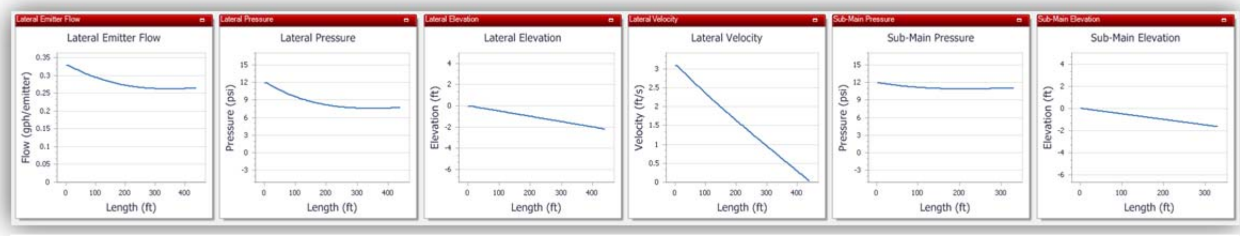


Figure 5 – Chart Tiles appear in minimized format at the bottom of the dashboard.

Alternatively, by clicking on the Chart Tile icon in the toolbar, each chart may be viewed individually in an expanded format, or with two, three, or four charts shown at a time, as shown in Figure 6:

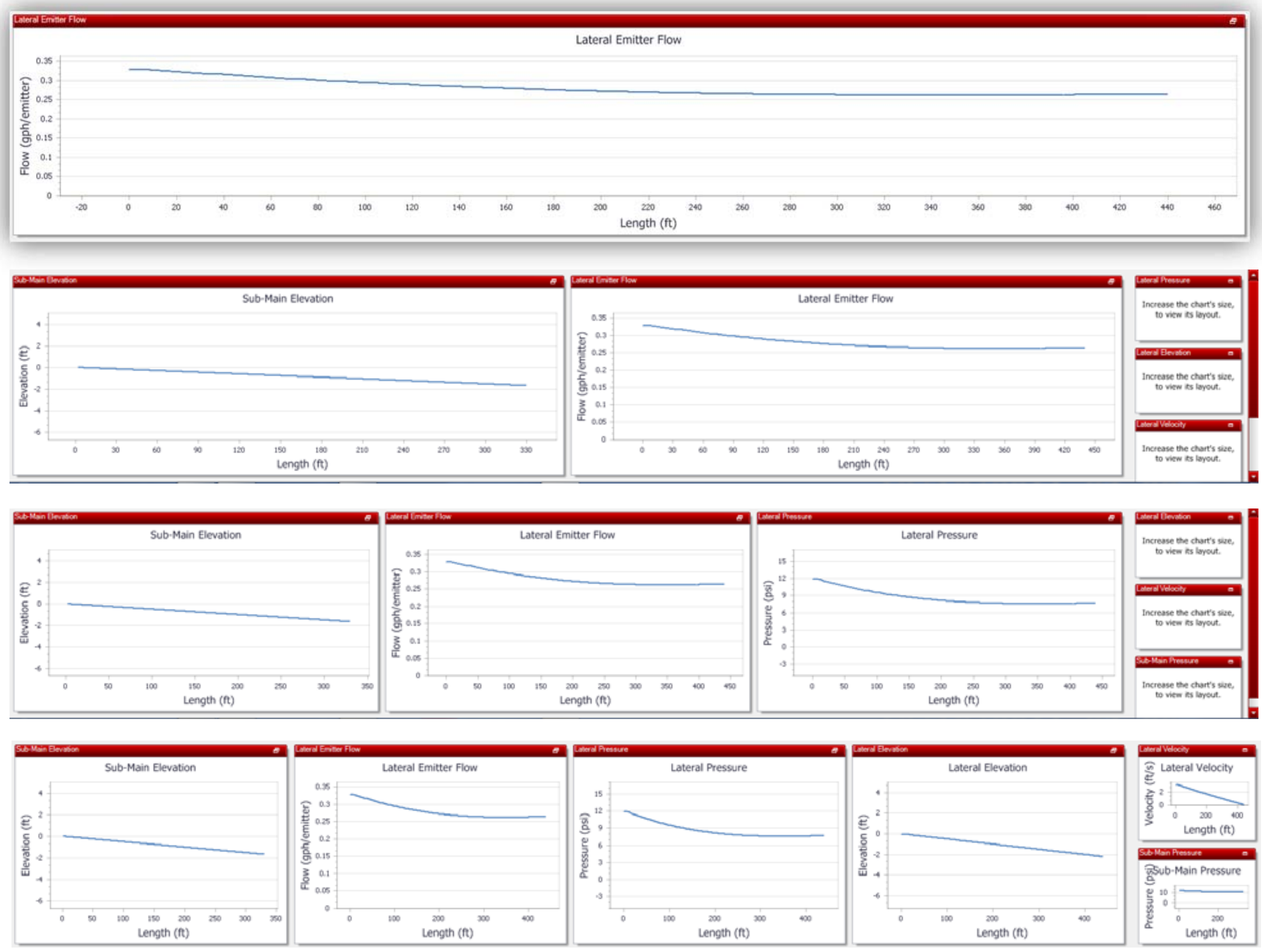


Figure 6 – Chart Tiles may appear individually or with two, three or four charts shown at a time.

The other key feature of the dashboard is the color-coded Uniformity Map which illustrates the percent flow deviation from average flow for each of the block designs. For example, a block design with high uniformity will have fewer colors than a block, design with poor uniformity. Figure 7 compares the uniformity map from a design using classic drip tape on the left with the uniformity map of a design using pressure compensating drip tape on the right. The design on the right is more desirable because it exhibits less flow variation, or less color variation, than the map on the left.

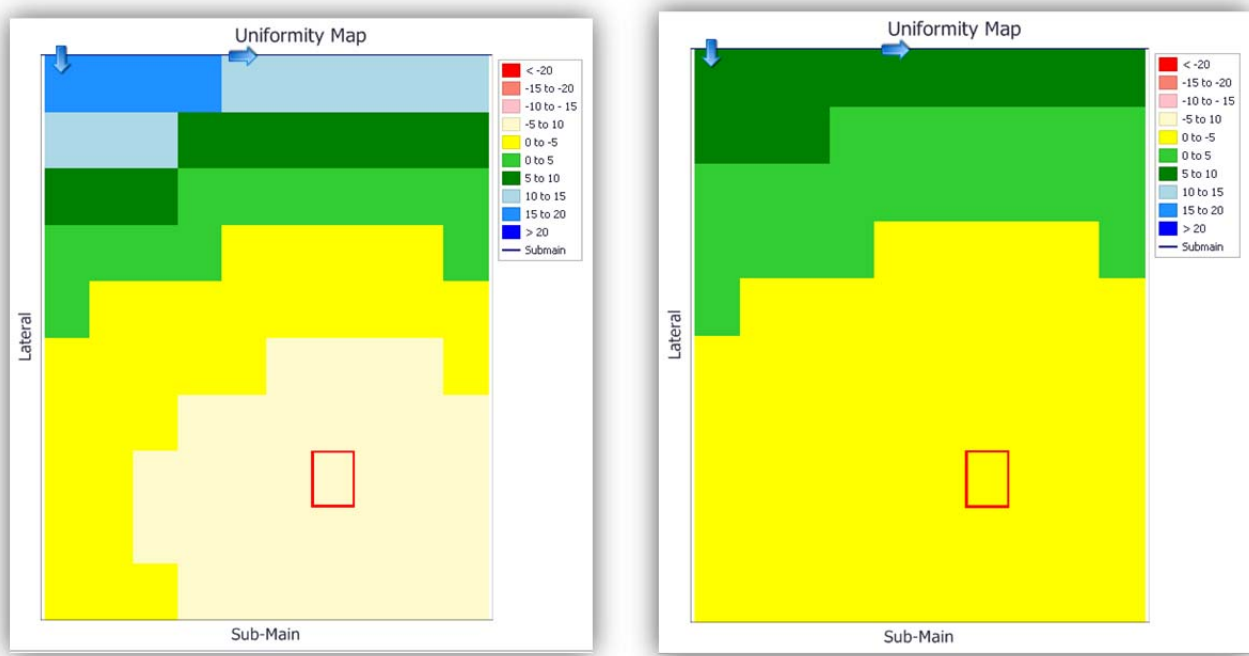


Figure 7 - Uniformity Maps for two different tape designs. The design on the left uses Aqua-Traxx Classic drip tape, the design on the right uses Aqua-Traxx PC drip tape.

In summary, the major advantage of using AquaFlow 3.2 software is that all lateral, sub-main and flushing outputs are instantly updated as inputs are changed by the designer. This includes the Output Overview, the Uniformity Map and the Chart Tiles. Thus, there is no need to toggle from one screen to another to view the results of user data input changes to length, slope, inlet pressure, manifold location, product selection, etc. This saves the designer time, and/or allows the designer to evaluate more options than ever before in an efficient manner. Now, let's compare two designs.

Default Block Design

When AquaFlow 3.2 launches, a default design appears on the screen with inputs selected and outputs displayed.

- The Lateral Selection uses Aqua-Traxx Classic drip tape part number EA5xx0867 on a .5% down slope, 440 foot length of run, 12 psi inlet pressure and the sub-main positioned at the top of the field. The Sub-Main is 4" Oval Hose, the sub-main runs along a .5% downhill slope, the sub-main length of run is 330 feet, the sub-main inlet pressure is 12 psi and the lateral row spacing is 48 inches apart.

  - The resulting Emission Uniformity (EU) for a single lateral line is 90.36%, and the EU for the entire block is 89.42%. All other Output data may be viewed beneath the Input data.
  - The Uniformity Map illustrates percent flow deviation from average for the block using color (yellow, green, and blue, in this case).
  - Select output data also appears in tiled graphs at the bottom of the page. To view any one to four of these in a larger format, select the "Chart Tiles" icon to the left of the Calculator in the Toolbar, and then click on the upper right hand corner of up to four tiles to enlarge them. Click on the "Chart Tiles" icon again to return to normal view.

- The Comparison lateral uses Aqua-Traxx PC drip tape part number EAP5xx0867 instead of Aqua-Traxx Classic – all other inputs remain the same. Note that the EU for a single lateral is now 93.16%, and the EU for the entire block is now 92.49%. Also, note that the Uniformity Map has improved and shows less color variation.

In this case, using a pressure compensating device helps the designer achieve a uniformity of 93.16% instead of 90.42%, a 3% difference.

- The Lateral and Sub-main flushing parameters may be viewed by toggling between the two choices. Note that the flushing velocity of the lateral is 1.48 feet per second (fps) when the inlet pressure is 12 psi, but that only 7.7 psi is required to achieve a flushing velocity of 1.0 fps.
- As noted above, select output data also appears in tiled graphs at the bottom of the page. To view any one to four of these in a larger format, select the "Chart Tiles" icon to the left of the Calculator in the Toolbar, and then click on the upper right hand corner of up to four tiles to enlarge them. Click on the "Chart Tiles" icon again to return to normal view.

Customers, Projects, Block Designs and Mainline Design

AquaFlow 3.2 may be used to create individual Block Designs as previously shown, but may also be used to design Mainlines that service multiple blocks. In this case, a Customer and Project must be created by the designer, and then multiple block designs assigned to that Project. A Mainline can then be associated with the project and designed to service the block with multiple segments.

- First, a Customer is created by choosing "Customer" from the Maintenance pull-down menu. This information will appear prior to the block and mainline designs when a Project is printed. Enter the required information and then click on Save and Close.
- Next a Project is created by choosing "Project" from the Maintenance pull-down menu. Create a Project name, and then choose the Customer that the Project is associated with. Now click on Save and Close.

- Now, a new Block Designs may be created. Choose “New Design” from the File pull-down menu or from the Toolbar. Name the design, enter the required information, and then click on Save & Close to view the results.
- For the next block, choose New Design again and repeat the previous procedure.
- When all blocks have been designed, a mainline may be designed to service each of the blocks. Choose “Mainline” from the Maintenance pull-down menu, or from the Mainline Icon on the toolbar. Then choose “New,” provide a name for the mainline design, and then associate it with a project so that it may be printed along with the block designs when Print Project is chosen. Now enter the elevation, flow, length, pressure, pipe type and pipe size information required for each mainline segment, beginning with the block furthest from the pump. The mainline report may then be printed and/or it may be saved. Figure 8 shows the data input screen for a two segment mainline that has been sized to supply water to the two blocks used in the previous examples as reported in Figures 11 and 12. In this example, the pump station is located 100 feet from the 2nd block.

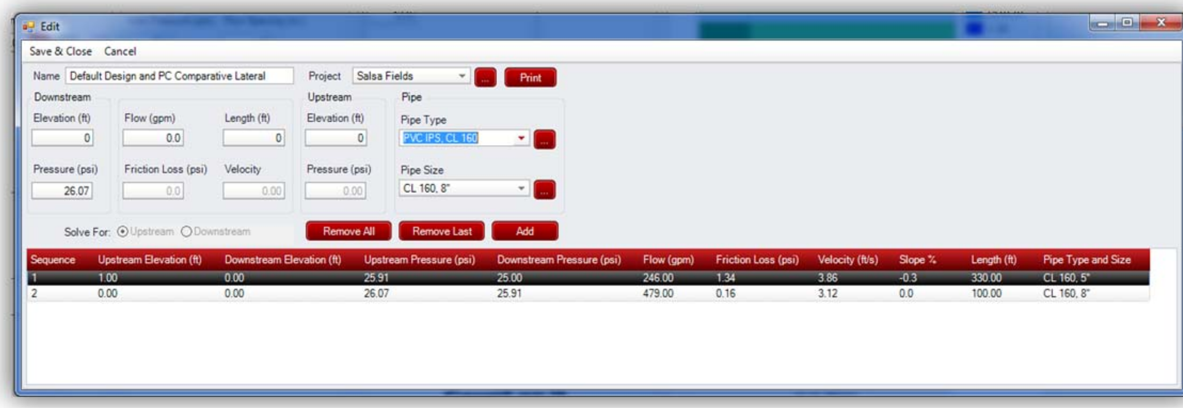


Figure 8 - Mainline Data Input Screen and Results

Printing Designs and Projects

Now any individual block design, or the entire project, may be printed, exported or emailed in pdf, html, mht, rtf, xls, xlsx, csv, text, or image file formats. From the pull-down menu, choose “Print Design” to print the Lateral Selection block design, the Comparison Lateral block design, or both, that are currently selected on the dashboard. Or, choose “Print Project” to print all the blocks and the mainline that is associated with the Project currently selected on the Dashboard. The report may then be customized with color and watermarks. Figure 9 shows the Design Report Options and the Watermark customization feature, and Figure 10 shows the report for the mainline associated with this project.

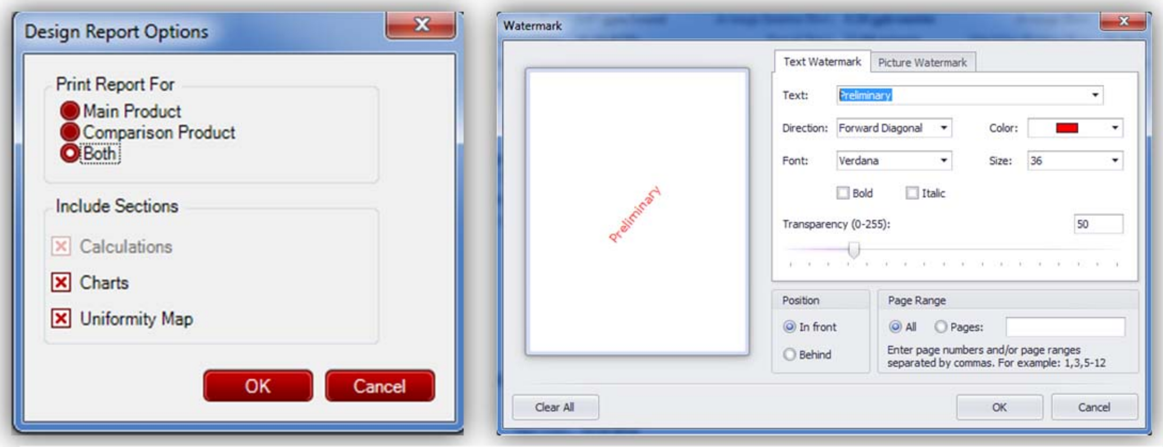


Figure 9 - Design Report Options and Watermark Options

Toro AquaFlow 3.0 Mainline Report

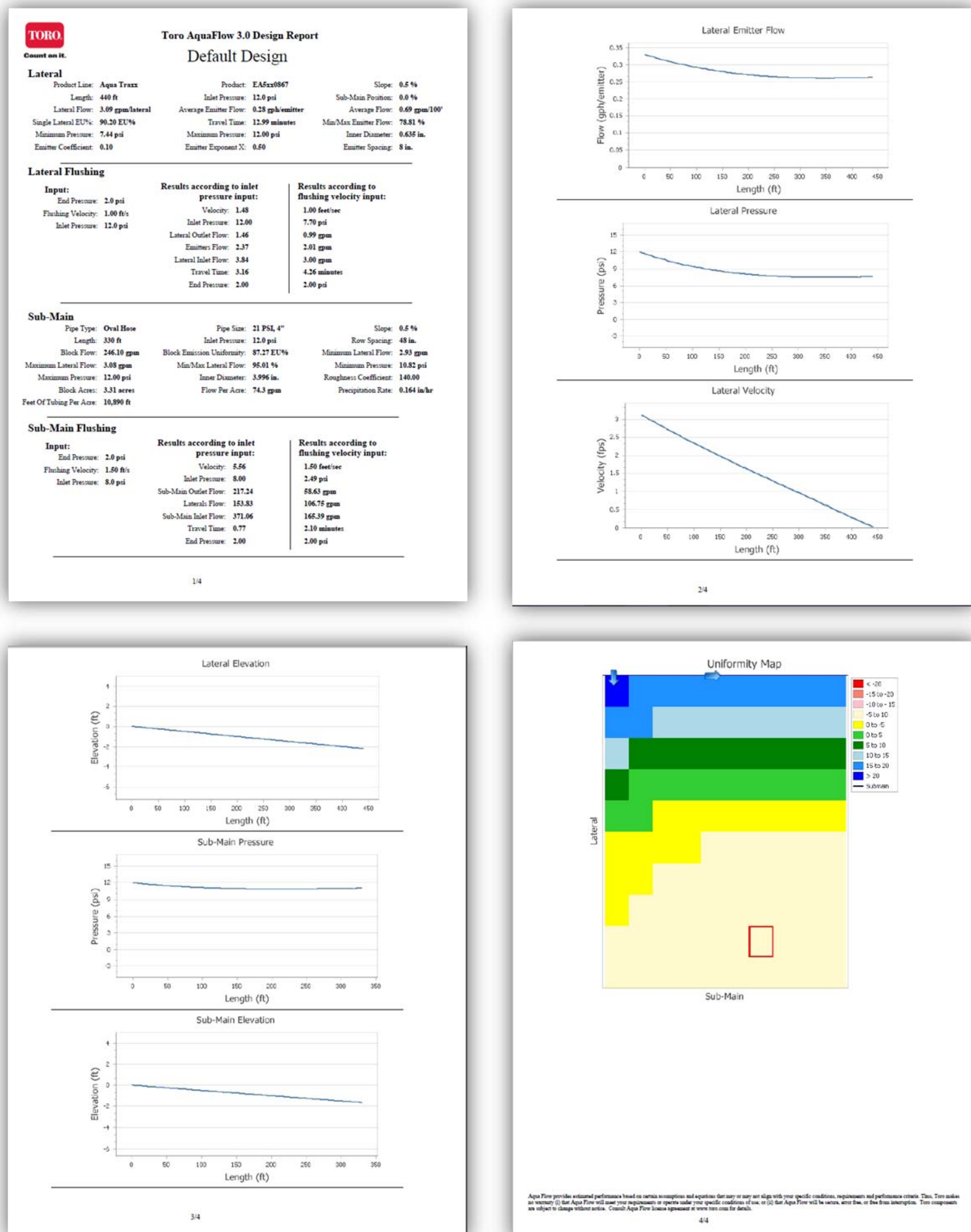
Default Design and PC Comparative Lateral

Sequence	Upstream Elevation	Downstream Elevation	Upstream Pressure	Downstream Pressure	Flow	Friction Loss	Velocity	Slope	Length	Pipe
1	1.00 ft	0.00 ft	25.91 psi	25.00 psi	246.00 gpm	1.34 psi	3.86 ft/s	-0.30 %	330.00 ft	CL 160, 5"
2	0.00 ft	0.00 ft	26.07 psi	25.91 psi	479.00 gpm	0.16 psi	3.12 ft/s	0.00 %	100.00 ft	CL 160, 8"

Figure 10 - Mainline Report

Finall7, Figure 11 shows the Lateral Selection Design Report output, and Figure 12 shows the Comparative Lateral Design Report output. All of these reports may be generated by choosing the “Print Project” option.

Lateral Selection Design Report using Aqua-Traxx Classic Drip Tape



Toro AquaFlow 3.0 Design Report

Default Design

Lateral

Product Line:	Aqua Traxx	Product:	EA5xx0867	Slope:	0.5 %
Length:	440 ft	Inlet Pressure:	12.0 psi	Sub-Main Position:	0.0 %
Lateral Flow:	3.09 gpm/lateral	Average Emitter Flow:	0.28 gph/emitter	Average Flow:	0.69 gpm/100'
Single Lateral EU%:	90.20 EU%	Travel Time:	12.99 minutes	Min/Max Emitter Flow:	78.81 %
Minimum Pressure:	7.44 psi	Maximum Pressure:	12.00 psi	Inner Diameter:	0.635 in.
Emitter Coefficient:	0.10	Emitter Exponent X:	0.50	Emitter Spacing:	8 in.

Lateral Flushing

Input:		Results according to inlet pressure input:		Results according to flushing velocity input:
End Pressure:	2.0 psi	Velocity:	1.48	1.00 feet/sec
Flushing Velocity:	1.00 ft/s	Inlet Pressure:	12.00	7.70 psi
Inlet Pressure:	12.0 psi	Lateral Outlet Flow:	1.46	0.99 gpm
		Emitters Flow:	2.37	2.01 gpm
		Lateral Inlet Flow:	3.84	3.00 gpm
		Travel Time:	3.16	4.26 minutes
		End Pressure:	2.00	2.00 psi

Sub-Main

Pipe Type:	Oval Hose	Pipe Size:	21 PSI, 4"	Slope:	0.5 %
Length:	330 ft	Inlet Pressure:	12.0 psi	Row Spacing:	48 in.
Block Flow:	246.10 gpm	Block Emission Uniformity:	87.27 EU%	Minimum Lateral Flow:	2.93 gpm
Maximum Lateral Flow:	3.08 gpm	Min/Max Lateral Flow:	95.01 %	Minimum Pressure:	10.82 psi
Maximum Pressure:	12.00 psi	Inner Diameter:	3.996 in.	Roughness Coefficient:	140.00
Block Acres:	3.31 acres	Flow Per Acre:	74.3 gpm	Precipitation Rate:	0.164 in/hr
Feet Of Tubing Per Acre:	10,890 ft				

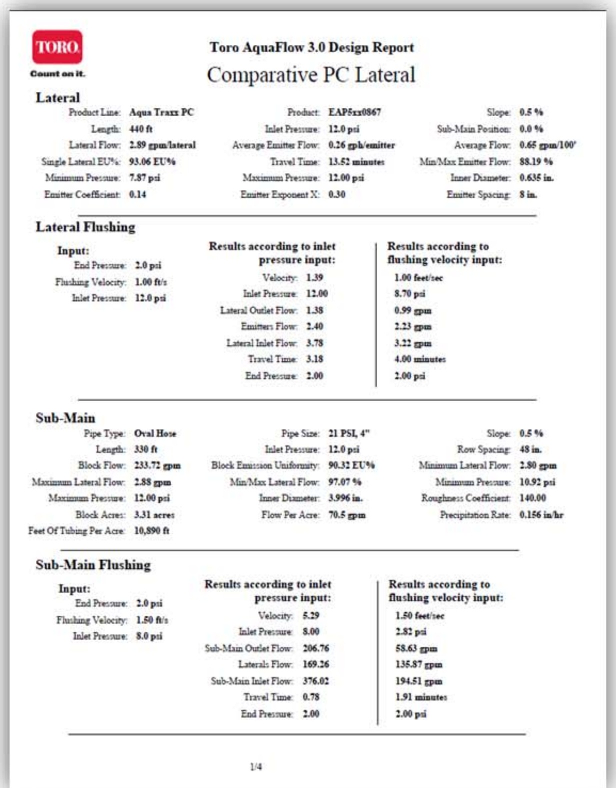
Sub-Main Flushing

Input:		Results according to inlet pressure input:		Results according to flushing velocity input:
End Pressure:	2.0 psi	Velocity:	5.56	1.50 feet/sec
Flushing Velocity:	1.50 ft/s	Inlet Pressure:	8.00	2.49 psi
Inlet Pressure:	8.0 psi	Sub-Main Outlet Flow:	217.24	58.63 gpm
		Laterals Flow:	153.83	106.75 gpm
		Sub-Main Inlet Flow:	371.06	165.39 gpm
		Travel Time:	0.77	2.10 minutes
		End Pressure:	2.00	2.00 psi

1/4

Figure 11 - Lateral Design Report Output

Comparative Lateral Design Report using Aqua-Traxx PC Drip Tape



TORO
Count on it.

Toro AquaFlow 3.0 Design Report

Comparative PC Lateral

Lateral

Product Line:	**Aqua Traxx PC**	Product:	**EAP5xx0867**	Slope:	**0.5 %**
Length:	**440 ft**	Inlet Pressure:	**12.0 psi**	Sub-Main Position:	**0.0 %**
Lateral Flow:	**2.89 gpm/lateral**	Average Emitter Flow:	**0.26 gph/emitter**	Average Flow:	**0.65 gpm/100'**
Single Lateral EU%:	**93.06 EU%**	Travel Time:	**13.52 minutes**	Min/Max Emitter Flow:	**88.19 %**
Minimum Pressure:	**7.87 psi**	Maximum Pressure:	**12.00 psi**	Inner Diameter:	**0.635 in.**
Emitter Coefficient:	**0.14**	Emitter Exponent X:	**0.30**	Emitter Spacing:	**8 in.**

Lateral Flushing

Input:		Results according to inlet pressure input:		Results according to flushing velocity input:
End Pressure:	**2.0 psi**	Velocity:	**1.39**	**1.00 feet/sec**
Flushing Velocity:	**1.00 ft/s**	Inlet Pressure:	**12.00**	**8.70 psi**
Inlet Pressure:	**12.0 psi**	Lateral Outlet Flow:	**1.38**	**0.99 gpm**
		Emitters Flow:	**2.40**	**2.23 gpm**
		Lateral Inlet Flow:	**3.78**	**3.22 gpm**
		Travel Time:	**3.18**	**4.00 minutes**
		End Pressure:	**2.00**	**2.00 psi**

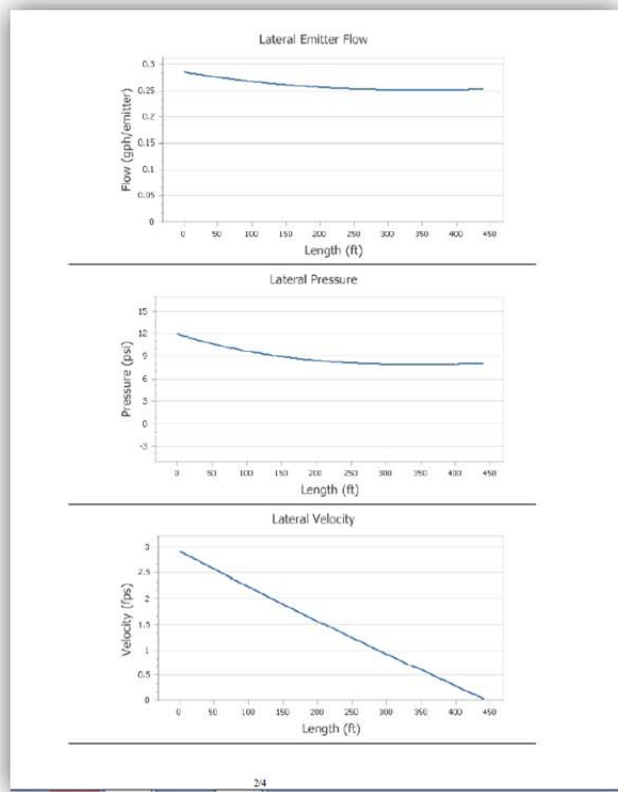
Sub-Main

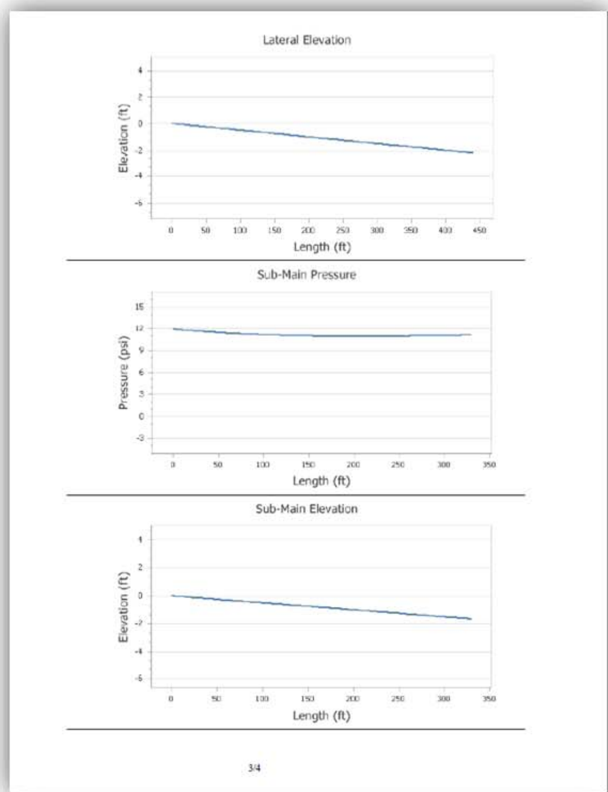
Pipe Type:	**Oval Hose**	Pipe Size:	**21 PSI, 4"**	Slope:	**0.5 %**
Length:	**330 ft**	Inlet Pressure:	**12.0 psi**	Row Spacing:	**48 in.**
Block Flow:	**233.72 gpm**	Block Emission Uniformity:	**90.32 EU%**	Minimum Lateral Flow:	**2.80 gpm**
Maximum Lateral Flow:	**2.88 gpm**	Min/Max Lateral Flow:	**97.07 %**	Minimum Pressure:	**10.92 psi**
Maximum Pressure:	**12.00 psi**	Inner Diameter:	**3.996 in.**	Roughness Coefficient:	**140.00**
Block Acres:	**3.31 acres**	Flow Per Acre:	**70.5 gpm**	Precipitation Rate:	**0.156 in/hr**
Feet Of Tubing Per Acre:	**10,890 ft**				

Sub-Main Flushing

Input:		Results according to inlet pressure input:		Results according to flushing velocity input:
End Pressure:	**2.0 psi**	Velocity:	**5.29**	**1.50 feet/sec**
Flushing Velocity:	**1.50 ft/s**	Inlet Pressure:	**8.00**	**2.82 psi**
Inlet Pressure:	**8.0 psi**	Sub-Main Outlet Flow:	**206.76**	**58.63 gpm**
		Laterals Flow:	**169.26**	**135.87 gpm**
		Sub-Main Inlet Flow:	**376.02**	**194.51 gpm**
		Travel Time:	**0.78**	**1.91 minutes**
		End Pressure:	**2.00**	**2.00 psi**

1/4





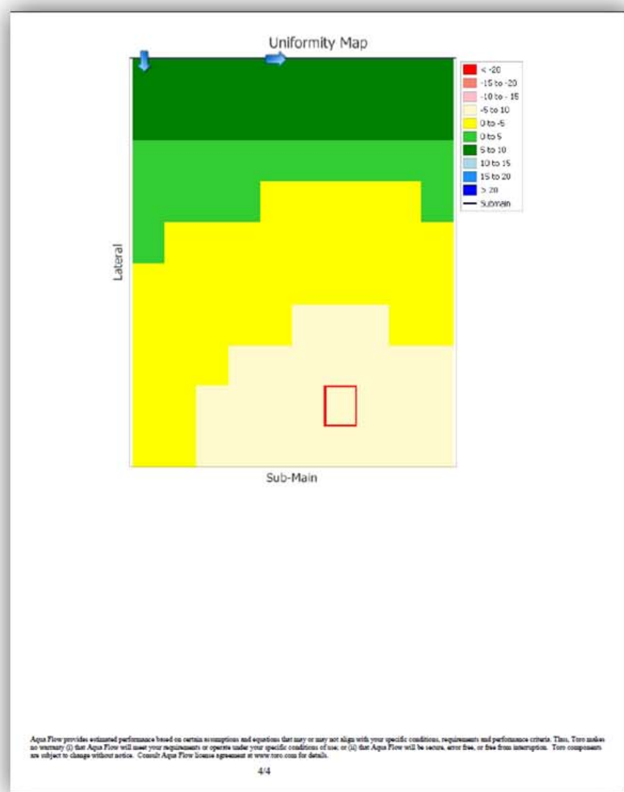


Figure 12 - Comparative Lateral Design Report

Conclusion

Making the right choices in drip irrigation design can be a tedious process. This is because the designer must choose the right inlet pressure, length of run and lateral, sub-main and mainline components, and then compare these numerous choices against one another for both irrigation uniformity performance and flushing performance. Previous drip irrigation design programs required toggling between screens to view the results of design choices.

Today, Toro's new AquaFlow 3.2 design assist software uses a unique dashboard approach that allows the designer to view both input and output data on one screen, and thus largely eliminates the need for toggling to other screens to evaluate choices. AquaFlow 3.2 also provides a color coded Uniformity Map and Chart Tiles of various operating parameters that instantly help the designer evaluate the results of input choices. Once a design is completed, it can then be saved and exported using various user-friendly file formats. By improving the efficiency and accuracy of drip irrigation design using AquaFlow 3.2, drip irrigation system field performance is improved as well.

AquaFlow 3.2 design assist software is available for free download upon approved registration at toro.com.

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BERMUDAGRASS YIELD RESPONSE TO IRRIGATION AND NITROGEN IN THE SOUTHEASTERN COASTAL PLAIN

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Abstract. *In the Southeastern region of the US, the cattle industry has a critical need for sustainable hay production. However, production is threatened by frequent short-term regional drought that can be mitigated by properly managed irrigation. In this study on Tifton 85 bermudagrass, irrigation management, nitrogen fertility levels, and harvest interval were evaluated for their impact on hay quality and yield. The optimal irrigation rate (100%) was set to maintain soil water potentials below -30 kPa. The reduced irrigation treatments received water in rates of 0, 33, and 66% of the 100% irrigation rate. In addition, each irrigation treatment had nitrogen rates of 168, 336, and 504 kg N/ha. The irrigation and nitrogen treatments were harvested at 4- or 8-week intervals. Over all harvests, nitrogen significantly increased bermudagrass hay yield. When irrigation was required, it significantly increased hay yields and hay yields increased linearly with increasing irrigation rate. The 4-week harvest interval was more responsive to irrigation. Additionally, we observed a linear relationship between non-irrigated bermudagrass hay yields and average soil water potential. As soil moisture was depleted, non-irrigated hay yields decreased 31 kg/ha per kPa. Thus, irrigation management should be critically assessed for its potential role in sustaining hay production in the southeastern Coastal Plain.*

Keywords. *Bermudagrass, Irrigation, irrigation management, Nitrogen, forage quality.*

INTRODUCTION

In most Southeastern US states, cattle production ranks in the top 10 leading commodities by cash receipts (USDA-ERS, 2011). This cattle production is vital to the regional economy. In this region, the cattle production industry has a critical need for sustainable hay production. Bermudagrass has become a major crop for forage and hay production crop in the Southeastern US (Muir et al., 2010; Alderman et al., 2011). However, hay production has been impacted by frequent short-term regional drought. This drought threat can potentially be mitigated by properly managed irrigation.

Most previous research on bermudagrass water use reported that periods of low rainfall or drought can impact production (Doss et al.,1962; Ashley et al.,1965; Marsalis et al., 2007; da Fonseca et al., 2007). Stone et al. (2010) reported that climate change and weather extremes were impacting water resources availability in the US and throughout the world. These weather extremes particularly short term droughts have the potential to impact bermudagrass hay production. The expectation of more frequent drought periods provides an incentive to investigate irrigation responses for stable bermudagrass hay production. Additionally, most of the previous research on bermudagrass irrigation was conducted with older cultivars that yielded about 75% of the current cultivars (Burton et al., 1993). Increased forage production with the newer cultivars suggests that reaching the genetic potential for yield may require more aggressive management. The objective of this research is to determine the impact of irrigation, nitrogen, and harvest interval on 'Tifton 85' bermudagrass hay yield and forage quality.

MATERIALS AND METHODS

In the spring of 2007, 'Tifton 85' bermudagrass was sprigged under a 6-ha site-specific center pivot irrigation system (Camp et al., 1998) on a relatively uniform Norfolk loamy sand (Typic Kandiudult) near Florence, South Carolina. In 2008 and 2009, an experiment was conducted to determine the impact of irrigation and nitrogen on bermudagrass hay yield and forage quality. Irrigation rate, nitrogen rate, and harvest intervals were evaluated. There were four irrigation treatments (0, 33, 66, and 100% irrigation). For each 100% irrigation application, the other irrigation treatments received a proportional application depth. In addition, each irrigation treatment had nitrogen treatments of 168, 336, and 504 kg N ha^{-1}. The irrigation and nitrogen treatments were harvested at 4- or 8-week intervals. The experimental design was a split-plot with harvest interval as main plots and the irrigation by N levels as subplots. The plot size was 20 m wide by 20 m long with four replicates (96 total plots). All treatments remained in the same plots for both years.

SOIL WATER POTENTIAL MEASUREMENT

Soil water potentials (SWP) were measured in all irrigation treatments and harvest intervals for the high N rate using tensiometers at two depths (0.30 and 0.60 m). Measurements were recorded at least three times each week. A 12.5 mm irrigation was initiated when SWP at the 0.30-m depth was below -30 kPa in the 100% irrigation plot with high N. The other irrigation treatments received a proportional application (0%, 33%, 66% of 12.5-mm). Additionally, if SWPs decreased below -50kPa, an additional 12.5 mm irrigation was applied if the rainfall forecast was less than 50%.

FERTILIZER APPLICATIONS

All nitrogen fertilizer was applied via fertigation through the center pivot in three annual split applications. In the spring, one-third of the total N per year for each treatment was applied at green-up, with the rest being applied in equal applications after the 8-week harvests. Low, medium, and high rates were 56, 112, and 168 kg N ha^{-1} per application. Total annual N application rates were 168, 336, and 504 kg N ha^{-1}. Phosphorus and K were uniformly applied in granular form across all plots each spring based on soil testing and recommendations of the Clemson University Extension Agricultural Service Laboratory. Fertilizer applied was 56 kg ha^{-1} P_2O_5 and 112 kg ha^{-1} K_2O in 2008, and 56 kg ha^{-1} P_2O_5 and 168 kg ha^{-1} K_2O in 2009. Nitrogen applications were applied with the minimal water application depths in order to minimize irrigation water applications to non irrigated plots.

HARVEST

The bermudagrass hay was harvested at 4- and 8-week intervals. In 2008, 4-week harvests occurred on 5/27, 6/24, 7/21, 8/18, and 9/18. The 8-week hay harvests were on 6/24, 8/18, and 10/14. There was not a 4-week harvest on 10/14 because of a lack of growth in those plots. In 2009, the 4-week hay harvests were on 6/22, 7/21, 8/17, 9/14, and 10/19. The 2009 8-week harvests were on 6/22, 8/17, and 10/19. In 2009, the 4-week bermudagrass treatments were delayed coming out of dormancy, so we postponed the initial harvest until June 2009 (8-weeks for this interval) to allow the crop to establish. Bermudagrass hay was harvested by cutting with a 3-m wide rotary mower/conditioner thorough the center of the plots. A 3-m windrow was then raked onto a small tarp and weighed for yield. A small sub-sample was collected for moisture calculations, C&N analysis, and forage quality testing. The rest of the plot was then mowed, dried, raked, baled, and removed from the field.

STATISTICAL ANALYSES

All data were statistically analyzed in SAS (Statistical Analysis System, SAS Institute, Cary, NC.) using a mixed model analysis. Each harvest in each year and total hay yield for the year were analyzed separately using the GLIMMIX procedure. Irrigation rate and N level were considered as fixed effects and replicates were considered random. Using the ESTIMATE command in GLIMMIX, linear, quadratic, and deviation from quadratic effects were tested for irrigation and linear and deviation from linear effects were tested for N.

RESULTS

HAY YIELDS

In 2008 and 2009, the mean bermudagrass hay yields for the rainfed treatments were 9.2 and 14.4 Mg ha^{-1}, respectively. Initial analysis indicated that the two years were significantly different, so we analyzed years separately. The differences between the years were mostly attributed to the differences in rainfall distribution. In 2008 and 2009, the total rainfalls for the growing season were 701 and 522 mm, respectively. However, the rainfall distribution and irrigation applications were different for each growing season (see Table 1). In 2008, the rainfall occurred during the latter part of the growing season. In 2009 the rainfall occurred during the first part of the growing season. In August and September 2009, the monthly rainfall was below normal and irrigation was required to meet crop demand. The total water applied was greater in 2008 than in 2009 due to the poor early season rainfall. In 2008, the 100% irrigation treatment received irrigation amounts of 152 mm and 191 mm for the 4- and 8-week harvest, respectively. The corresponding 2009 100% irrigation treatments received 89 and 102 mm of irrigation for the 4- and 8-week harvest, respectively.

Table 1. Number of irrigations (n) and rainfall for the 2008 and 2009 bermudagrass hay 4 and 8 week harvest intervals over the irrigation treatments.

		month													
		5		6		7		8		9		10		Total	
		n	Rain	n	Rain	n	Rain	n	Rain	n	Rain	n	Rain	n	Rain
		(mm)													
Harvest	year														
4	2008	2*	83	3	39	2	133	0	165	0	199	0		7	619
	2009			0	251	0	97	0	63	2	29	5	82	7	522
8	2008			11	122			4	299			0	281	15	701
	2009			0	251			1	161			7	111	8	522

* The 100% irrigation treatment received 12.5 mm per irrigation. The other irrigation treatments received a percentage of that amount per irrigation.

IRRIGATION TREATMENTS

Irrigation generally increased bermudagrass hay yields both annually and across cutting intervals. Irrigation linearly increased bermudagrass hay yields in five of ten 4-week harvests and in two of six 8-week harvests. In 2008, the overall yearly 4-week harvest hay yields were significantly linearly correlated with the irrigation treatments (Table 2). Likewise, the individual 4-week harvests were also positively linearly correlated with irrigation treatment for all harvest except the August 2008 harvest. The August harvest was negatively correlated to irrigation treatment. During the growth period for this harvest, no irrigation was applied because of

Table 2. Mean 2008 and 2009 bermudagrass hay yields for the 4 and 8 week harvest intervals over the irrigation treatments.

			month						
			5	6	7	8	9	10	Total
			Yield (kg ha^{-1})[1]						
Harvest	year	Irrigation							
4	2008	0	1552	664	1455	1904	3063	.	8638
		33	1547	1151	1939	1570	3090	.	9297
		66	1666	1332	2303	1546	3350	.	9893
		100	1733	1450	2160	1352	2966	.	9504
		Linear	*	**	**	**	ns		**
		Quadratic	ns	*	ns	ns	ns		**
	2009	0	.	6986	3253	2441	733	1514	14927
		33	.	6684	3003	2402	886	1734	14708
		66	.	6328	2985	2605	812	2101	14831
		100	.	7172	3055	2654	947	2293	16121
		Linear		ns	ns	ns	ns	**	ns
		Quadratic		*	ns	ns	ns	ns	ns
8	2008	0	.	2889	.	2789	.	4171	9755
		33	.	3327	.	3036	.	4062	10426
		66	.	3349	.	2749	.	3535	9658
		100	.	3869	.	2819	.	3783	10446
		Linear		*		ns		ns	ns
		Quadratic		ns		ns		ns	ns
	2009	0	.	6000	.	5103	.	2710	13813
		33	.	5481	.	5380	.	3248	14109
		66	.	6188	.	4543	.	3624	14356
		100	.	5439	.	5173	.	4313	14925
		Linear		ns		ns		**	ns
		Quadratic		ns		ns		ns	Ns

[1] *, and ** indicate contrast was significant at the P<0.10, and 0.05, respectively. ns indicates no significant difference.

plentiful rainfall. Additionally, the plant nitrogen removed in the hay had a similar negative trend possibly indicating that 165 mm of rainfall during that harvest interval may have leached available N below the root zone.

During the first part of the 2008 growing season, rainfall totals were below normal and irrigation was required to keep soil water levels at an adequate level. This corresponded to the observed low soil water potential values from May to July (DOY 142 to 191, Figure 1). Both the 30-cm and 60-cm deep soil water potentials followed the same trend (60-cm soil water potential data not shown). During this time period, the 100% irrigations applications (12.5 mm per application) were generally not large enough to keep the 30-cm deep soil water potential <-30 kPa, but soil water potential were still greater than -50 kPa and did not trigger the additional 12.5 mm irrigation.

The overall 2008 8-week hay yields were not correlated to the irrigation treatments. Only in the first 8-week harvest in June 2008 did yield significantly increase with irrigation. Because of sufficient rainfall, the remaining two 8-week harvests were not correlated to irrigation treatments.

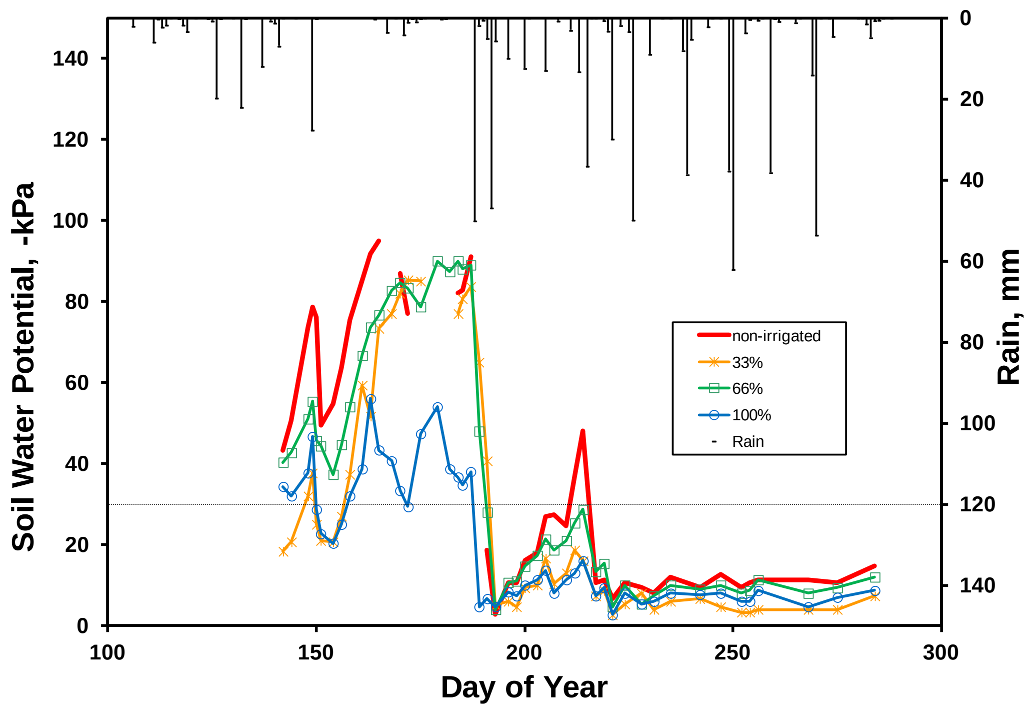

Figure 1. Soil water potentials for the 2008 4-week harvest interval, 30-cm irrigated bermudagrass.

In 2009, the overall 4- and 8-week hay yields were not correlated to the irrigation treatment. Only the, October 2009 4- and 8-week harvests were correlated to irrigation treatment. The 2009 rainfall distribution was at or above normal for most of the early growing season. However in late August and September (DOY 225-272), the rainfall was well below normal. This low rainfall contributed to both the low observed soil water potentials (Figure 2) and the yield response to increasing amounts of irrigation.

Additionally, we plotted yield versus average soil water potential for the harvest period for both harvest intervals and each irrigation treatment across both years (Figures 3 and 4). For the 4-week harvest interval, the non-irrigated soil water potentials were correlated to yield (r^2=0.68,

Figure 3), but the irrigated soil water potentials were not (r^2=0.33, 0.31, and 0.44 for the 33, 66, and 100% treatments, respectively). The 8-week harvest intervals generally had slopes similar to the 4-week harvest intervals (Figure 4). The 8-week non-irrigated SWPs were less correlated (r^2=0.49) than the 4-week results. Interestingly, the non-irrigated 4- and 8-week harvest intervals had similar slopes, -30.4 and -31.8 kg ha^{-1} kPa^{-1}, respectively. The 8-week irrigated SWPs had a very poor correlation to yield (r^2=0.29, 0.08, and 0.01 for the 33, 66, and 100% treatments, respectively), yet the 33% and 66% treatments had slopes similar to the 4-week harvest interval. The poor correlations were also expected because the range of SWP values was much smaller and corresponded to the increasing irrigation application depth treatments.

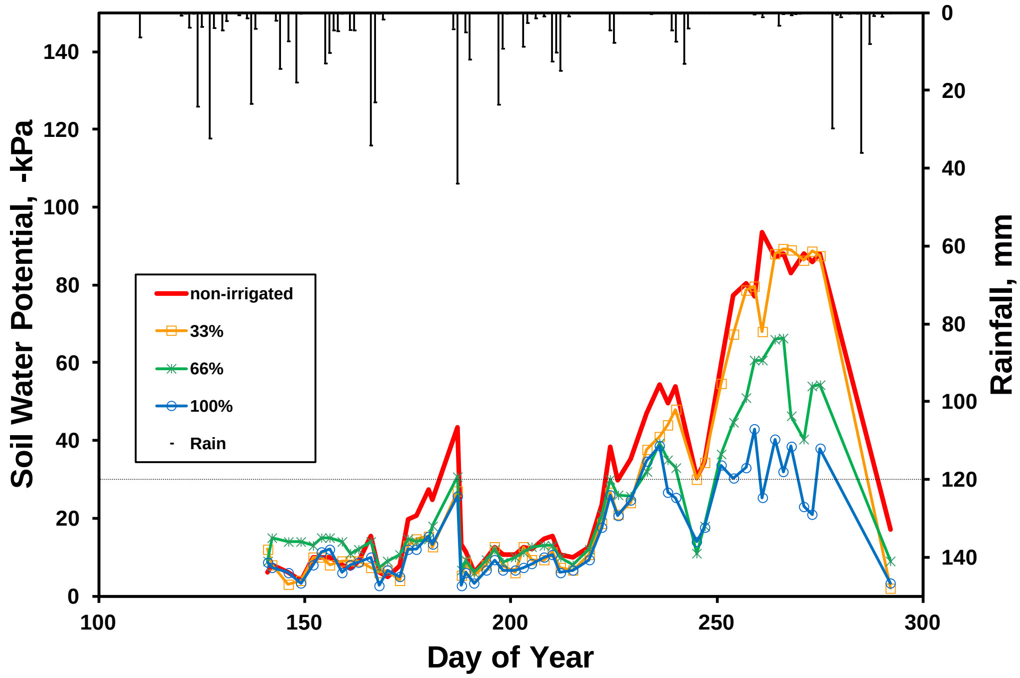

Figure 2. Soil water potentials for the 2009 4-week harvest interval, 30-cm irrigated bermudagrass.

NITROGEN RATES

For both years and over both harvest intervals, the annual hay yields had a significant linear correlation to increasing N rate (Table 4). Additionally, the 2008 4-week, and 2009 8-week harvest interval hay yields had significant deviation from linear trend to increasing N rate. The correlation between increased N rate and yields has been observed in other studies (Burns et al., 1985; Mandebvu et al., 1999; Adeli et al., 2005; da Fonseca et al., 2007; Garcia et al., 2008; Alderman et al., 2011).

For the individual 4- and 8-week harvest intervals, all had linearly correlated yield increases with increasing N rates. Only the 4-week harvest interval harvest in September 2008 and the 8-week harvest in June 2009 had a significant deviation from linear response.

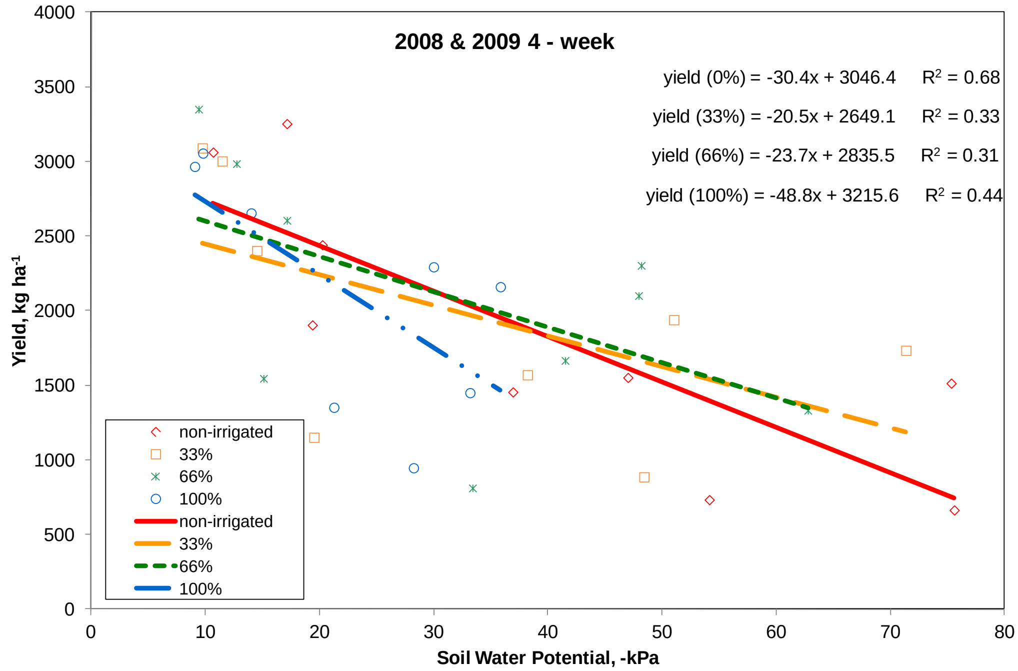

Figure 3. Bermudagrass hay yields as influenced by soil water potential for the 4-week harvest intervals.

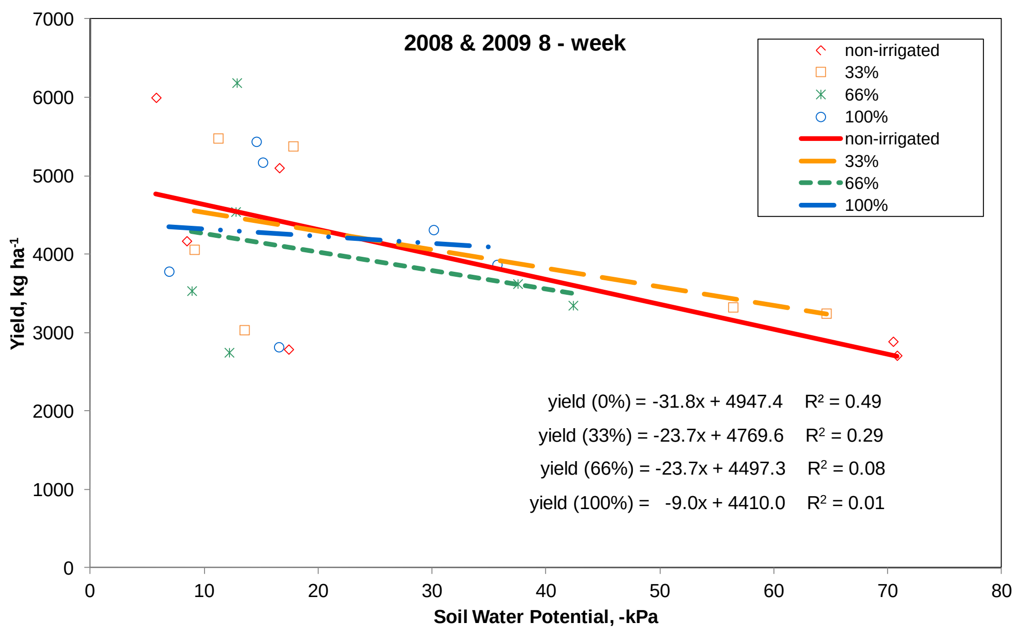

Figure 4. Bermudagrass hay yields as influenced by soil water potentials for the 8-week harvest intervals.

Table 4. Mean 2008 and 2009 bermudagrass hay yields for the 4 and 8 week harvest interval over the nitrogen treatments.

			month						
			5	6	7	8	9	10	12
			Yield (kg ha^{-1})[1]						
Harvest	Year	Nitrogen							
4	2008	1	1273	673	1245	1421	1989	.	6601
		2	1701	1038	2225	1527	3422	.	9913
		3	1899	1737	2422	1907	3941	.	11842
		Linear	**	**	**	**	**		**
		Deviation from Linear	ns	ns	ns	ns	**		*
	2009	1	.	5579	2330	2026	304	1307	11545
		2	.	7023	3200	2373	951	1964	15510
		3	.	7777	3692	3178	1278	2461	18386
		Linear		**	**	**	**	**	**
		Deviation from Linear		ns	NS	ns	ns	ns	ns
8	2008	1	.	2679	.	1969	.	2537	7185
		2	.	3300	.	3109	.	4045	10445
		3	.	4097	.	3617	.	5081	12975
		Linear		**		**		**	**
		Deviation from Linear		ns		ns		ns	ns
	2009	1	.	4817	.	3853	.	2172	10843
		2	.	6275	.	5275	.	3669	15219
		3	.	6239	.	6022	.	4580	16841
		Linear		**		**		**	**
		Deviation from Linear		*		ns		ns	**

[1] *, and ** indicate contrast was significant at the P<0.10, and 0.05, respectively.
ns indicates no significant difference.

HARVEST INTERVALS

Harvest intervals did not have a significant impact on the annual bermudagrass hay yields. In 2008, the 4- and 8-week hay yields were 9.3 and 10.1 Mg ha^{-1}, respectively. In 2009, the 4- and 8-week hay yields were 15.1 and 14.3 Mg ha^{-1}, respectively. The most noticeable difference between the harvest intervals was for the June, August, and October harvests. Since nitrogen fertilizer was applied at 8-week intervals, these harvests were typically lower in yield than the May, July, and September harvests possibly due to lower available N.

More 4-week harvests had significant yield increases with irrigation than 8-week harvests. This could be the result of short term droughts (7 to 20 days). Sheridan et al. (1979) documented that in the Southeastern Coastal Plain that there was a 50% chance of a 20 day drought annually. A drought of this length would more likely impact a 28 day harvest interval than a 56 day harvest interval. In North Carolina, Stone et al. (2008) reported on the impact of several short term drought periods on bermudagrass production and found similar trends in hay yields.

CONCLUSIONS

We conducted a two year study to investigate the response of bermudagrass hay production to irrigation and nitrogen application rates. In both years, when irrigation was required to maintain soil water potentials greater than -30 kPa, bermudagrass hay yields significantly increased with increasing water application rate treatment. During these cutting intervals, the 4-week 100% irrigation treatments increased mean yields 612 kg ha^{-1} per cutting over the non-irrigated treatment and the 8-week 100% irrigation treatment increased mean yields 1600 kg ha^{-1} per cutting. Additionally, for the non-irrigated bermudagrass hay yields, we observed a linear relationship between hay yield and soil water potential. Non-irrigated hay yields were shown to decrease (-31 kg ha^{-1} kPa^{-1}) as soil water was depleted. Both nitrogen and irrigation were found to positively impact bermudagrass hay production. Bermudagrass can benefit from timely supplemental irrigation applications to boost yields and maintain forage quality. Bermudagrass irrigation management to maintain soil water potentials above -30 kPa can increase yields and sustain production levels in the southeastern Coastal Plain.

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ON-FARM STRATEGIES FOR REGULATED DEFICIT IRRIGATION TO MAXIMIZE OPERATIONAL PROFIT POTENTIAL

by

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ABSTRACT

Municipalities and other water providers are expected to seek increasing amounts of agricultural water to meet the demand created by projected future growth along the Front Range of Colorado and within the South Platte Basin. Farms often are acquired outright, the water rights parted off, and the original decree changed to municipal use—a process commonly referred to in the regional water community as “buy and dry”. Concerned about the negative effects of buy and dry on agriculture, rural communities, and the environment, the State of Colorado has funded research into alternative, less permanent methods for transferring water from agriculture. This paper describes a simulation and optimization model that a farmer-user may utilize to evaluate successful future farming operations using a smaller amount of consumptive use water. Optimization algorithms are used within a new Model to evaluate a farmer-considered package of changed practices which may include: regulated deficit irrigation, new crops, dryland crops, permanent or rotational fallowing of fields, and crop rotations. Model results help a farmer understand the options and whether or not they would want to consider changed practices in the future in return for an additional and low-risk revenue stream for the overall farm operation.

KEYWORDS

Irrigation engineering

Water rights quantification

Consumptive use

Evapotranspiration

Expert system

Mathematical optimization

Farming practices

INTRODUCTION

In 2003, the State of Colorado initiated a significant water resources planning effort called the Statewide Water Supply Initiative (SWSI) for the purpose of projecting water supply availability and needs for each of Colorado's river basins in 2030 (Gimbel 2010). Most basins in Colorado were found to be forecasting water shortfalls in 2030. For the South Platte Basin, the SWSI report forecasted a population growth of 65% which equates to 2,000,000 additional people by 2025 and an associated water supply need of an additional 400,000 acre feet. The South Platte is already over appropriated. Transbasin transfers and new storage are essentially no longer feasible or extremely difficult options at best, because of planning and permitting obstacles. The prevalent presumption within the regional water community is that the additional 400,000 acre feet will likely come from irrigated agriculture – water transfers from irrigated agriculture to municipal and industrial (M&I) uses (Colorado Water Conservation Board. et al. 2004).

This population growth and water demand dynamic is also playing out in other states in the West and other basins in Colorado in the form of municipal acquisition of whole farms -- along with the water -- through outright willing-seller, willing-buyer purchases. The consumptive use (CU) portion of the water right is often 100% removed from the farm and the use of the water is most often changed to M&I use. The farm is dried up into perpetuity. This process of permanent dry up is often referred to as "buy and dry" in water planning circles and in the popular press (Gimbel 2010). Some of the municipalities who have availed themselves of this practice are now saying publicly that they do not wish to continue with the practice of buy and dry because of the impact on the rural community and the cumulative negative push back from many sectors. At the same time, municipalities are actively looking for sound alternatives to buy and dry that provide predictable water supply, or what is commonly known as "firm yield", for the cities (CDM 2010).

Alternatives to buy and dry – also called alternative transfer methods (ATMs) – and often cited in the SWSI reports and elsewhere include:

1. Interruptible water supply agreements.
2. Rotational fallowing.

3. Water banking.
4. Reduced consumptive use through changed irrigation and farming practices.

Interruptible water supply agreements involve temporary arrangements where agricultural water rights can be used for other purposes. Agricultural irrigation is temporarily halted under terms of an agreement in order to make a prescribed and contracted delivery (Trout Witwer & Freeman. 2004). An advantage of this approach is that an interruptible water supply agreement is defined by State Statute (37-92-309). It can be initiated under a contract arrangement between a water right holder (aka “water righter loaner”) and a water user (aka “water right borrower”) – likely a municipality -- needing water to cover a water shortfall in a given year. The statute defines the water transfer frequency to three out of ten years – hence strengthening the temporary aspect of this approach. The Colorado State Engineer is responsible for the oversight and approval of interruptible water supply agreements (Colorado Statutes 2003).

Rotational fallowing is conceived as a one to multi-year fallowing arrangement where, for instance, a fraction of the participating farms in a mutual irrigation company or other entity agree to fallow their farms, and thereby transfer a predetermined amount of water to a municipal interest (HDR Engineering 2007). Multi-year fallowing involves closely prescribed reseeding and establishing a suitable grass cover to protect the fallowed ground from erosion.

Water banking is a Colorado legislature-authorized approach to storing or setting aside water so that it can be leased to an alternative need during drought or when the water would otherwise not be put to beneficial use (Gimbel 2010). A water bank was initiated and exists in the Arkansas Valley. However, to date, it has not received enough user acceptance to make it truly viable.

Reduced consumptive use through changed farm water management involves identifying a quantified portion saved from the historic crop CU on a farm or farms. This saved portion of the CU would then be parted off and moved toward non-farming beneficial uses. The remaining historical CU would be used to continue agricultural operations. Ideally, this process would be carefully planned and monitored to ensure future farming operations (Gimbel 2010).

The Model (aka Sustainable Water and Innovative Irrigation Management® or SWIIM®) described here focuses on the fourth ATM option noted previously, namely reduced CU through one or more changed farming practices.

CONSUMPTIVE USE AND WATER BALANCES

The estimation of CU can be complex and time-consuming. The historic water diversions (water measured through the mutual irrigation company's river diversion) and season of use can generally be found in the data base of the State of Colorado's South Platte Decision Support System. However, historic cropping data and irrigated acreages are not so easily found, resulting in the need for background investigations of all available historic records over a suitable period of record. Historic irrigation practices, estimates of irrigation efficiency, and delivery efficiency (canal seepage) also come into play with the CU calculations and must be determined or estimated from available records.

This process of estimating historic CU on the South Platte has been facilitated by the Integrated Decision Support Consumptive Use (IDSCU) model that was developed at Colorado State University for the purpose of assisting engineers and attorneys in the development of databases and the calculation of historic ET. Essentially all of the methods and equations for calculating ET can be evaluated and compared when using the IDSCU model (Garcia 2009). In recent years, this model has been almost exclusively used by water resource engineers in Colorado Water Court change cases.

A water balance of the river, canal, or the farm is a useful means of understanding the sources of and the destinations of water. Figure 1 provides a conceptual rendering of water balance analysis, from the river diversion downstream to the on-farm distribution system. Basically, what this illustrative graphic shows is what happens to water once it is diverted into a ditch or canal for irrigation purposes. In many ditch company operations, the character of the water changes significantly as one moves downstream in the canal. Colloquially, some would say that the "color" of the water changes; a reference to where the water came from, or where it is bound, or its decreed use.

After diversion into an earthen canal, the diverted flow immediately begins to diminish because of conveyance losses, the most notable of which is seepage. Other losses are attributable to phreatophytes and evaporation from the water surface. Seepage can be quite significant especially over the full length of the canal and is likely the single highest source of loss in earthen canals. Most seepage returns to the river as subsurface flows and the time it takes to actually arrive at the river is a function of distance from the river and the characteristics of the alluvium. This seepage can vary considerably over the length of a canal as well. With a water right change case, this historic surface and subsurface return flow pattern must be maintained into the future.

Moving downstream through the canal, some water returns to the river via the end of the canal as wastage or operational spill. Some canals have historically diverted a generous amount of water to assist with practical canal operations. It is easier to deliver equitable flows to canal headgates, especially those at the end of the canal, if the canal is flowing nicely with excess water that can be returned to the river for other downstream users.

Continuing reference to Figure 1, a headgate delivery to the farm has similar water balance characteristics as with the main canal. However, the headgate delivery frequently represents the point at which the company's delivery responsibility ends and the individual farmer's responsibility begins. Downstream of the farm headgate, there are often on-farm conveyances (ponds and delivery ditches) from which there are losses, and again, those loses are most notably seepage that constitutes historic return flows that must be maintained.

Once water is delivered to on-farm irrigated fields, and on through the associated farm irrigation systems, the key elements of irrigation water can be identified as consumptive use, surface return flows, and subsurface return flows. Within the consumptive use amount, there is a proportion that may be appropriately termed "conserved" or "saved" or "set-aside" CU. This amount is the water that might be considered for its higher economic value. The total amount of quantified CU can be evaluated in terms of a water budget. The CU volume can be considered, along with old or new proportional uses, and within the confines of the water budget.

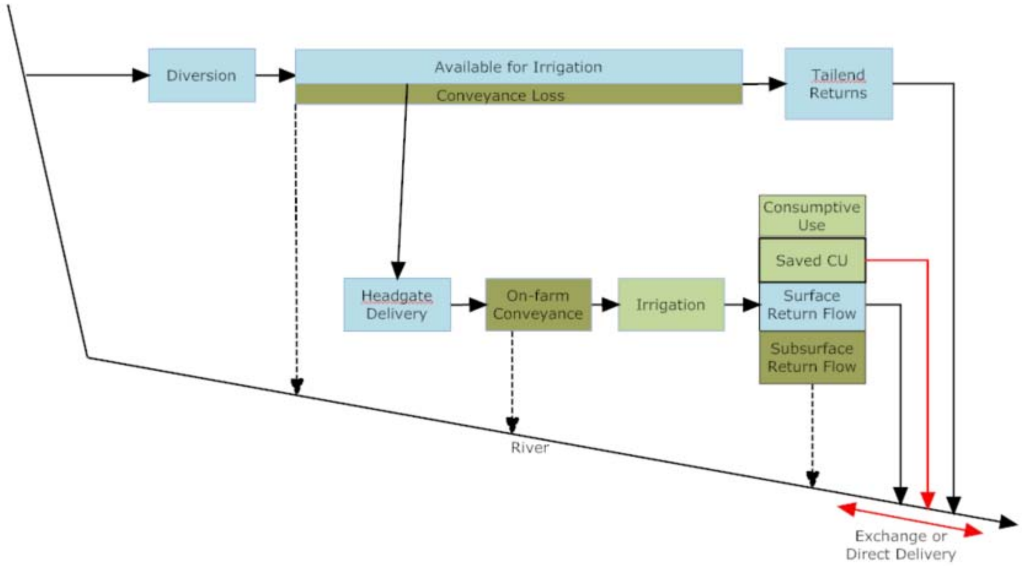


Fig.1 Depiction of the elements of surface water delivered to the farm via canal

The average historically diverted water to the farm can be characterized as consumptive use, surface return flow, and subsurface return flow (Figure 2). Crop consumptive water use is the amount of water transpired during plant growth plus what evaporates from the soil surface and foliage in the crop area. The portion of water consumed in crop production depends on many factors, including whether or not the availability of water is limiting evapotranspiration. Additionally, CU varies with soil texture, crop varieties, and so on.

Once an estimated or a fully decreed consumptive use is known for a given water right, it opens up the potential to consider options for how the CU might be utilized or allocated differently in the future. This could involve addressing differing demands and, for that matter, market forces. The consumptive use could be allocated to a new use priority or some balance between old and new priorities. The consumptive use can now be viewed more rationally as an on-farm CU water budget with potential alternative uses. Obviously, and in point with the overall premise of this paper, a new use of the CU might be to portion off some of this "saved" CU to a municipal or environmental water user for suitable monetary consideration.

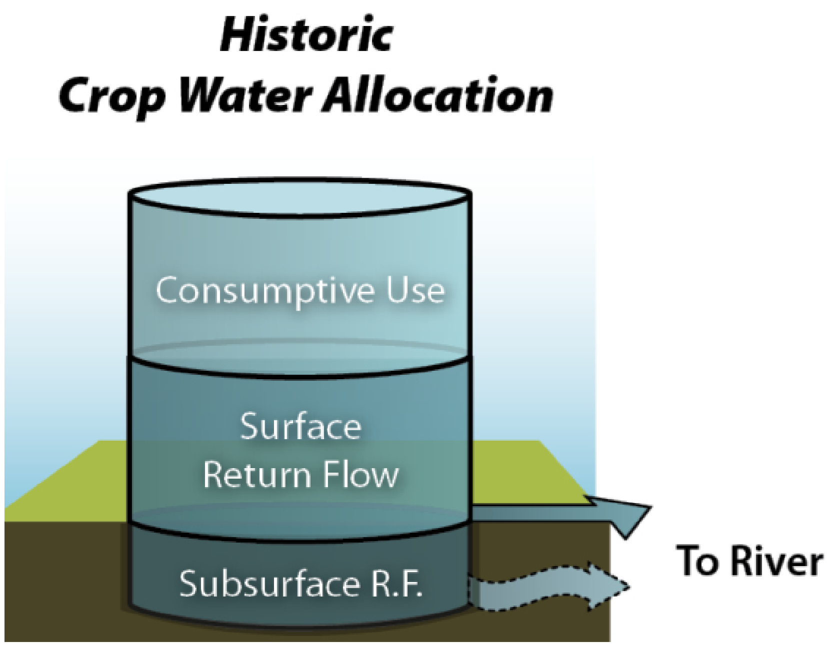


Fig.2 Depiction of the primary named use of water in a water balance on the farm

It is good to review some key framing points. First, it is clear that water resources in the South Platte Basin are currently over appropriated. Second, a significant amount of the water to sustain the anticipated and continued population growth in the basin is likely to come from agriculture in one way or another. Third, many observers are not viewing so-called "buy and dry" options as a suitable method of obtaining municipal and industrial (M&I) water, primarily because of the tremendous negative impact on rural communities. Fourth, and central to this dissertation, alternatives to "buy and dry" may be attractive to those acquiring future water supply as well as those currently owning water rights.

A Model has been developed to assist farmers in evaluating alternative irrigation or cropping practices, in order to help understand the options and whether or not they would want to consider changed practices in the future in return for an additional revenue stream for the overall farm operation.

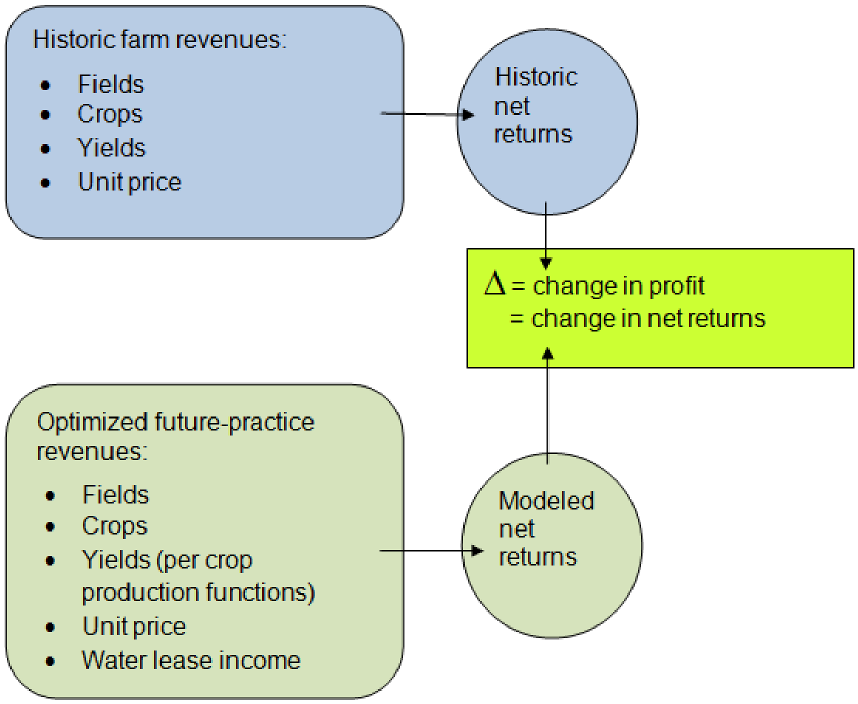
Net return is the income from an investment after deducting all expenses from the gross income generated by the investment. Net returns in a farming operation are defined to be farm revenues minus the fixed operating costs. Net return has also been defined as the return to land and management. On the other hand, farm net returns, by definition, does not include land costs, interest, taxes, and other costs that are fixed regardless of irrigation decisions (Martin 2010).

$$net\ returns\ = revenue - fixed\ operating\ costs$$

This approach to using net returns as the primary means of comparing one model run to another is affected by some important farmer client issues as well. These include:

1) The availability of detailed farm financial data.
2) Potential reticence of the farmer to disclose detailed personal financial data, even if readily available.
3) Time considerations – the desirability of farmers to quickly enter input data to see some preliminary results, combined with their possible lack of willingness to spend hours on data entry and setup.

Figure 3 graphically shows the inputs to the model and the optimized (modeled) net return. A successful run of the optimization model indicates the projected net return associated with the crops to be grown along with predicted crop yields, the practices to be adopted, and the anticipated unit prices. This modeled net return can then be contrasted with the historic net return from the farming operation.



Net Returns = Revenue – Fixed Operating Costs

Notes:
1) Fixed operating costs are those costs that will not change with a change in practices.
2) Net returns is the contribution to profit and overhead.

Fig. 3 Optimized future practices compared to historic practices on the basis of net returns

The Model was first developed in Excel using the Solver add-in to Excel. More specifically the Premium Solver Platform was used so as to not significantly limit the number of fields or optimization defining constraints. As the developing Excel spreadsheet became functional and stable, the Model was brought into a web interface so that:

1) The program could be delivered to a farmer-user by downloading it from a server.
2) The user interface could be narrowly and cleanly defined, better than in Excel, to enhance the user experience.

THE MODEL

The Model utilizes farmer-user inputs for the simulated farming operation to mathematically optimize future farming operations against a quantified or presumed consumptive use water budget for the farm. Default data are available with the program data base as extracted from the National Agricultural Statics Service (http://www.nass.usda.gov/). A successful run of the model constitutes a "scenario" that can be evaluated.

The farm simulation input is easy to use by simple point and click entry of boundaries over the top of aerial imagery to outline the farm itself and existing or proposed fields, then inputs such as planned "willing to grow" crops and practices are added. When finished, the farmer has a precise computer-generated map of the farm that becomes the basis for planning and running scenarios.

Inputs include fields (up to 20 fields), acceptable crops and irrigation practices that the farmer is willing to consider by field (up to 18 combinations). Practices for farmer-consideration include full irrigation, deficit irrigation, dryland crops, and fallowing. Default values for crop market price and per crop input costs are used or any of the default inputs can be changed as may be desirable from the farmer's experience or perspective.

With input entry completed, a mathematical optimization is performed based on those inputs to provide a scenario that can be named and saved. Optimization output data compares historical net revenues with the forecast of net revenues based on the scenario. The forecast of net revenues will likely be less than the historic net revenues but the lease value of the consumptive use water is forecast as well. The lease value of the water, when added to the forecast net revenues, will likely exceed the historic net return.

Several screen captures exemplify the user experiences in exercising the model as found in the web-delivered and server based program offering. Figure 4 shows the geographic information system (GIS) style field data entry screen. The user does not need to know GIS programing or input features in order to input field data into the system. Data entry is facilitated by using intuitive point and click tools. Field boundaries can be input, color coded, named, and resultant acreage returned. The input screen can be set up to show attributes of interest by picking suitable attributes from the list on the left.

Figure 5 shows the user interface for inputs of crops that the farmer is willing to grow along with the acceptability, or not, of certain practices to the farmer. Also, note the input of maximum and minimum acreage for both irrigated and dryland crops on this input screen.

Figure 6 shows the reported results of the optimization run and indicate the projected net return given the farmer inputs.

SUMMARY

An optimized package of irrigated farming practices, based on a consumptive use (CU) water budget, can help demonstrate the feasibility and basic concept of selling or leasing a fraction of a water right to make farming more attractive, profitable, and sustainable.

Through an engineering study of crops, acreages, evapotranspiration, and water diversions, water rights in Colorado can be quantified for the historic consumptive use. Quantification is necessary if one is to change the water right from the decreed type of use, place of use, point of diversion, and season of use. The costly engineering and legal effort to change a water right (aka transaction cost) is undertaken in order to bring greater value to the right and increase flexibility for future use. Municipal, industrial, and environmental interests are actively searching for senior surface water rights, usually agricultural water rights that can be moved from agriculture to other purposes. This process of locating and moving a water right often results in farms being bought up and permanently dried up. This is a dynamic that is occuring in the South Platte River Basin and believed to not be in the best interests of the larger community or in maintaining a sustainable irrigated agricultural system. Total water management is an admirable concept that can be furthered using the optimization Model and the follow-on implemented system. Use of this technology helps answer the question of how to bring more cooperation between conflicting users, share valuable water resources, bring benefits to the community, and sustain a viable agricultural economy.

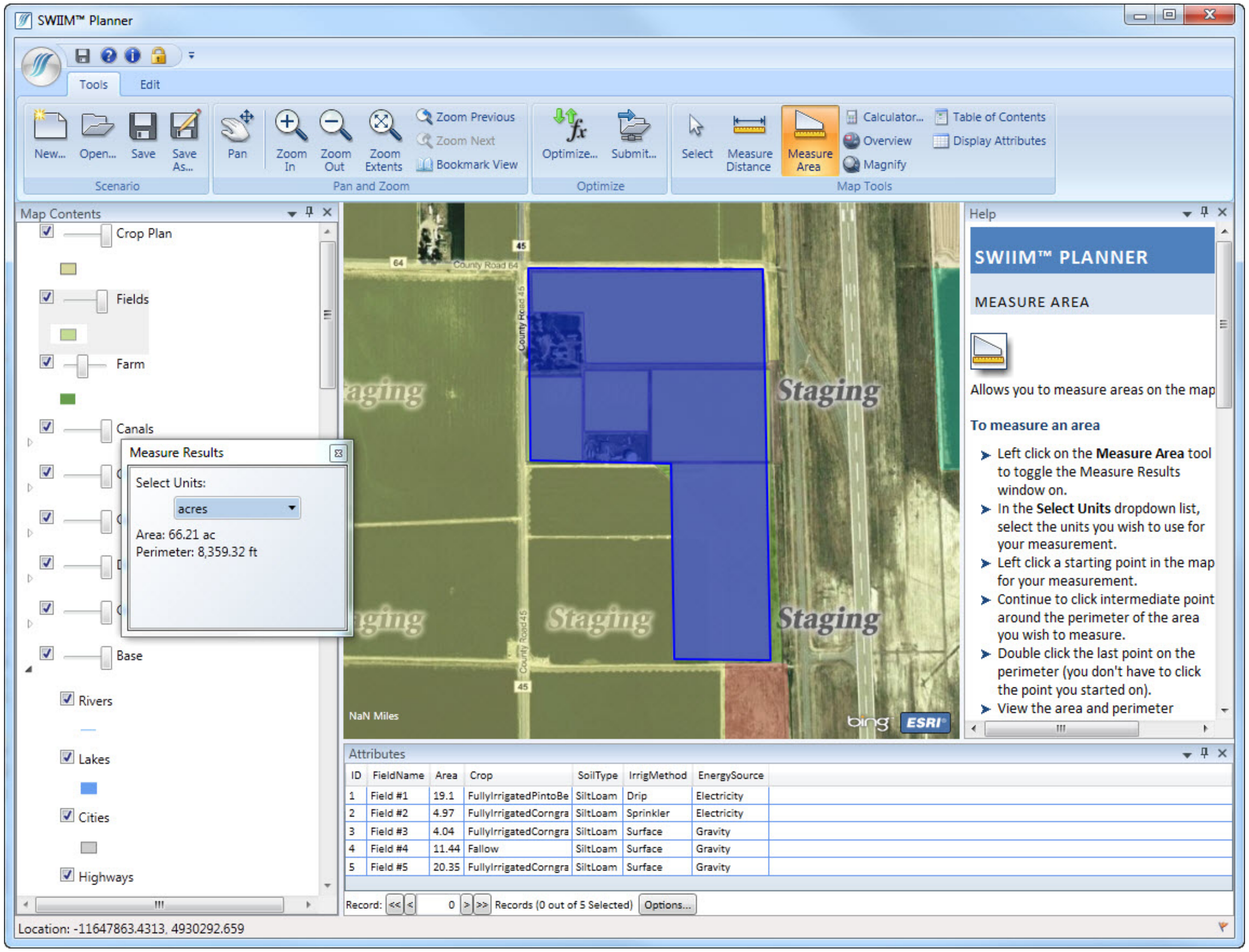


Fig. 4 Optimization program GIS-like data entry screen

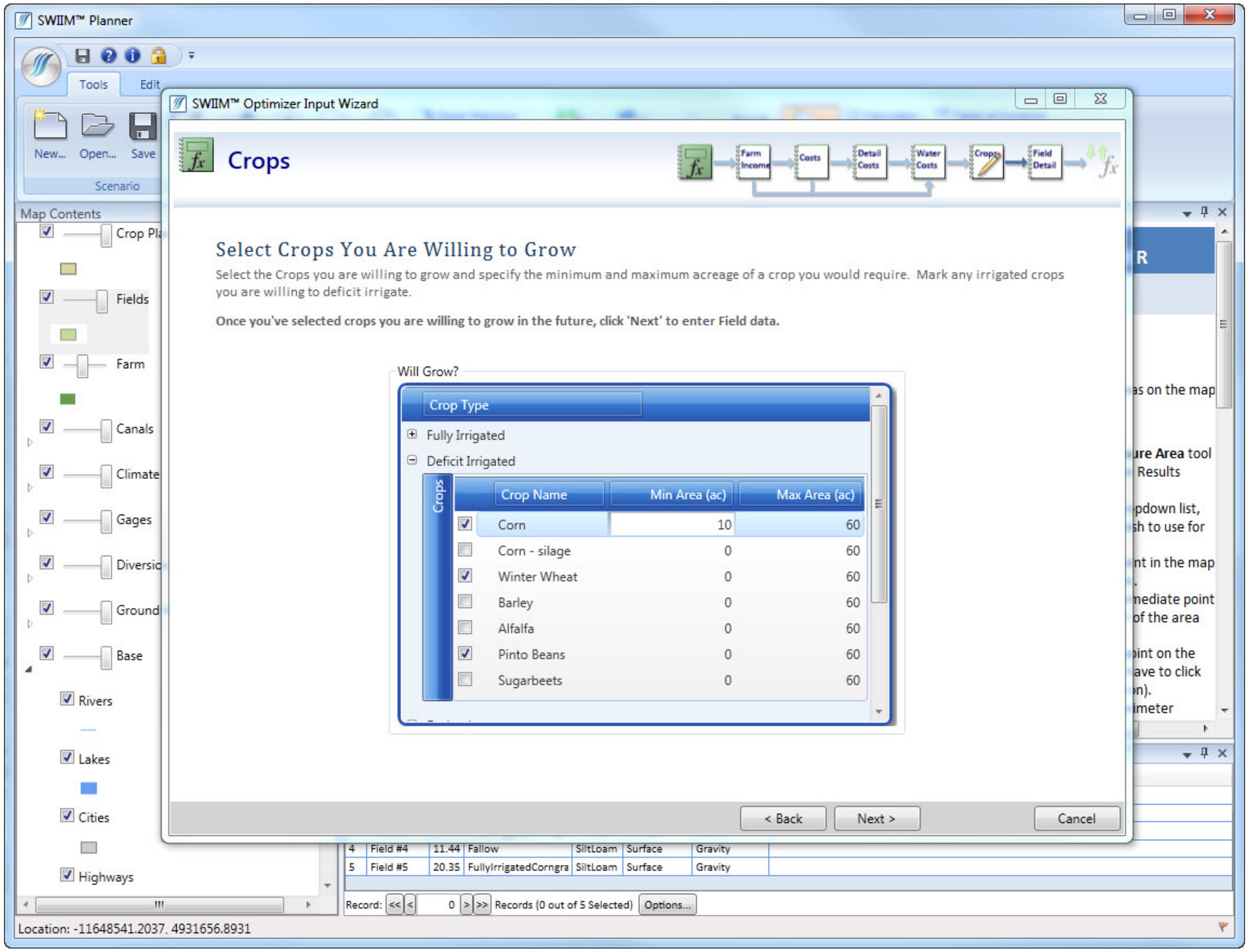


Fig. 5 Optimization program input screen for crops and acceptable practices

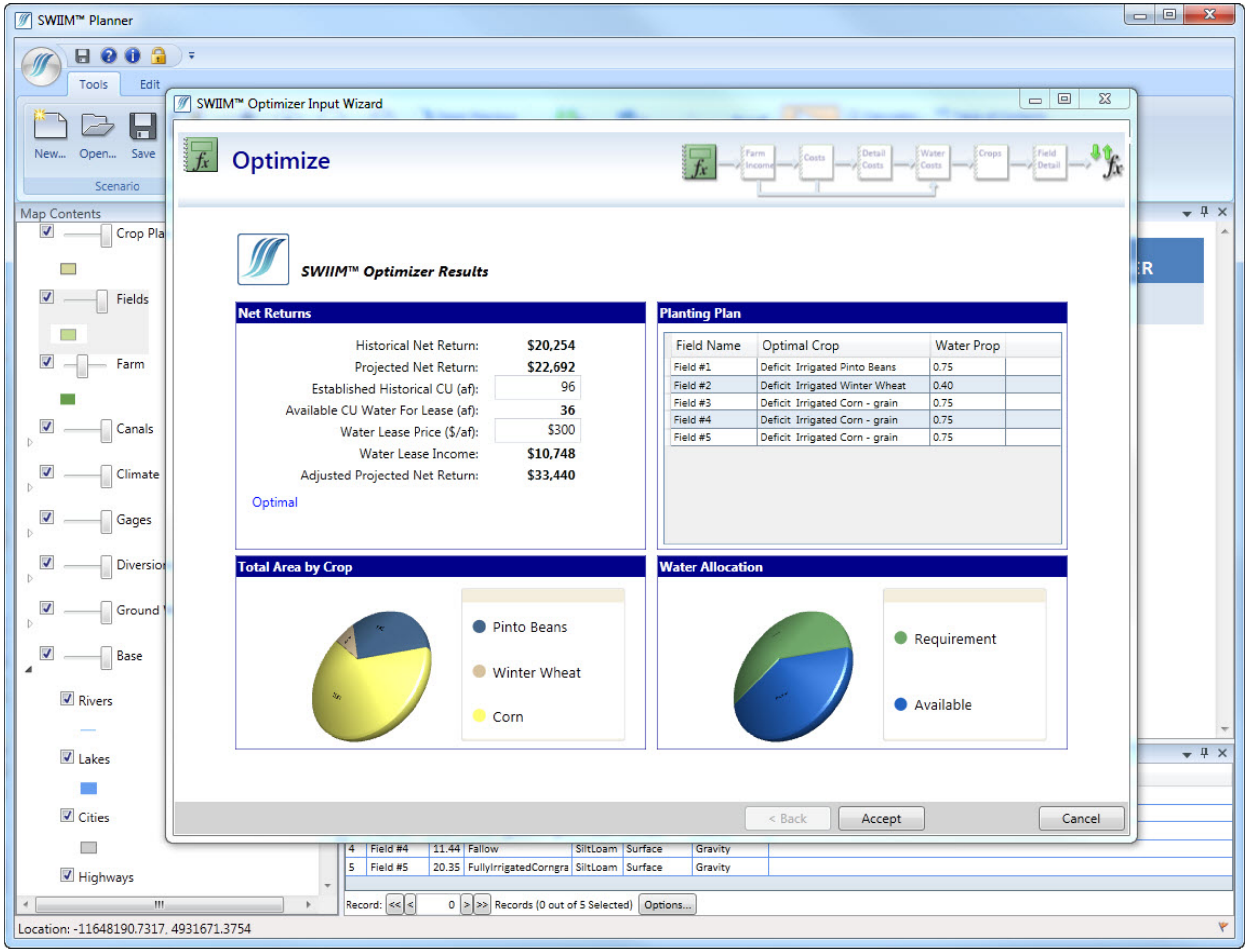


Fig. 6 Optimization program output report screen indicating the modeled net returns based on user inputs

The Model, a simulation and optimization model as described, is researched and developed to allow a farmer user to view the CU water differently than in the past. Namely, the CU can be viewed within a farm water budget and evaluated for future uses. Might the farmer wish to part off a portion of the CU, under contract, to a higher economic value driven by non-agricultural interests? The optimization of future net returns, based on adoption of a package of changed farming practices, allows for a comparative analysis. Multiple runs of the model can provide understanding of the potential and, in effect, a useful sensitivity analysis.

Farmers operating under a senior surface irrigation right within a ditch system may wish to work together as a new cooperative group, or as a subset of shareholders, wishing to implement this technology. This affords a larger block of CU water, and a larger block will be more attractive to the leasing entity. The ditch company or the cooperative would become the managing entity. The resulting implemented system would include SCADA hardware, software, and instrumentation suitable to farm management objectives, ditch company management objectives, and Colorado State Engineer operational reporting requirements.

Some farmers will not consider using this technology. Some farming operations are profitable, sustainable, and doing well in today's agricultural economy. Other farmers are farming in a marginal financial sense. An operational change using these technologies might help increase profits, allow for, or support irrigation system improvements, and otherwise help those farmers stay in business and continue providing significant regional economic benefits.

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Optimizing Sprinkler Irrigation for Cold Protection in Strawberries

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Abstract. *Sprinkler irrigation has been used effectively for cold protection in strawberries. While an application rate of 0.25 inches per hour is recommended to protect plants from cold damage, the effectiveness of alternative rates for adequate protection has not been studied. The objective of this study was to determine the effect of varying sprinkler supply pressure and spacing on strawberry yield and quality under freeze conditions. Five treatments were evaluated using sprinkler irrigation, two system pressures: 50 and 30 psi, and two sprinkler spacings: 48 ft. and 40 ft. The experimental design was a complete randomized block design with three replications and repeated measurements. Initial results showed significant yield differences between the irrigated treatments and the control. Recovery capability from the cold events among the irrigated treatments did not differ significantly. Only irrigated treatments showed a linear increase in the yield after each cold event.*

Keywords. Cold protection, Sprinkler irrigation, Strawberries, Variable pressure.

Optimizing Irrigation for Cold Protection in Strawberries

Introduction

The United States of America is the largest strawberry producing country in the world. Florida is the second largest strawberry-harvesting state, where 10 to 15 percent of the total U.S. crop is produced (FAOSTAT, 2011). Hence, strawberries represent an important crop for this state, where, the strawberry growing season occurs during the winter; therefore, plants can suffer cold damage when the air temperature falls to critical levels.

Irrigation is the primary method used for fruit, vegetable and nursery cold protection. Particularly, sprinkler irrigation has been used effectively for cold protection in strawberries for several decades (Locascio et al., 1967). In recent years, due to the unusual number of cold events, the ground water supplies have been stressed by the large volumes of water withdrawn in order to protect the plants from cold damage in the Dover/Plant City region.

Overwatering plants can cause several problems such as resource depletion, nutrient leaching, and increased plant diseases. The critical situation presented in this area provoked the need to create best management practices on water use.

Current cold protection recommendations are based on 1960's modeling for citrus nurseries and it is not clear if these recommendations are for advective (i.e., windy) or radiative freeze events. An application rate of 0.25 inches per hour (in h^{-1}) is recommended to protect the plants from freeze damage; however, the effectiveness of alternative rates for freeze protection have not been tested. Lower sprinkler application rates may provide adequate cold protection and result in less pumping required.

Latent heat

Latent heat is the chemical energy stored in the bonds that join the water molecules together, which is converted to sensible heat when water condenses, cools or freezes, increasing the temperature of the surrounding environment (Snyder, 2000b). The heat released through fusion is 80 calories per gram or 0.32 BTU and the temperature when water is freezing will be close to 32 ºF, even though the surroundings may be colder. Therefore, an equilibrium temperature state will be established as long as the mixture of water and ice is present and the temperature remains close to 32 ºF (Harrison et al., 1987). Under the latent heat transfer principle, the heat loss from the plant to its immediate environment is substituted by the sensible heat and the heat of fusion associated with the water, providing protection to the plants from frost or freeze damage using sprinkler irrigation (Harrison et al., 1987).

Critical temperatures and cold damage

"A "frost" is the occurrence of an air temperature of 32 °F or lower, measured at a height of between 1.25 and 2.0 m (4.1 and 6.6 ft.) above soil level, inside an appropriate weather shelter" (Snyder and de Melo Abreu, 2005). Some avoidance factors (e.g. supercooling and concentration of ice nucleating bacteria) might provoke a freezing of the water within plants. *"A "freeze" occurs when extracellular water within the plant freezes (i.e. changes from liquid to ice).*

Damage on the plant tissue depends on some tolerance factors (e.g. solute content of the cells) (Snyder and de Melo Abreu, 2005).

When extracellular ice forms inside of the plants, the frost event is converted into a freeze event. However, freeze injury is present when an irreversible physiological condition occurs causing death or malfunction of the plant cells after falling below a critical value (Snyder and de Melo Abreu, 2005). This temperature varies within varieties and species at the same temperature and phenological stage. Critical temperatures for strawberries are defined in Table 1.

Table 1. Strawberry critical temperatures at different crop stages calculated using dew point and wet bulb temperatures (°F). Table used to determine turn-on and turn-off times for the AC treatment irrigation system.

	Strawberry critical temperature at			
Crop stage	Tight bud	Popcorn	Fruit	Open blossom
	Critical temperature or Wet bulb temperature (ºF)			
Dew point (°F)	23	28	29	31
32	-	-	-	-
31	-	-	-	31.0
30	-	-	-	31.7
29	-	-	29.0	32.3
28	-	28.0	29.6	32.9
27	-	28.6	30.2	33.5
26	-	29.2	30.8	34.0
25	-	29.7	31.3	34.6
24	-	30.2	31.8	35.1
23	23.0	30.7	32.3	35.6
22	23.5	31.2	32.8	36.1
21	24.0	31.7	33.3	36.6
20	24.4	32.1	33.7	37.0
19	24.9	32.6	34.2	37.5
18	25.3	33.0	34.6	37.9

Adapted from (Snyder, 2000).

Sprinkler irrigation for cold protection

Drip and sprinkler irrigation are the two systems used to produce strawberries in Florida. Sprinkler irrigation is typically used by Florida growers for crop establishment during 10 to 14 days after transplanting for between 12 and 14 hours per day giving an approximately of 16-24 inches (Santos et al., 2010). In addition, sprinklers are used for frost protection.

Objectives

The objective for this study is determination of the effect of varying sprinkler supply pressure and spacing on strawberry yield and quality under freeze conditions.

Materials and Methods

This study was conducted from September 2011 to April on the 2012 at the Plant Science Research and Education Unit near Citra, Florida. Pre-formed planting beds were established (28 in. wide at the base, 24 in. wide on the top, and 10 in. high) on an Arredondo Sand soil with 0.5% organic matter and pH of 6.2. Soil was fumigated with methyl bromide/chrolopicrin (50/50, v/v) and after, beds were covered with black high-density polyethylene mulch 1.25 mm thickness. Pre-plant fertilizer 10-10-10 at 400 lb/ac was used. Fertilization and pest control was done according to the requirements of the crop (Botts et al., 1995). Fertigation was applied through a 5/8 inch drip tape line 10 ml thickness with 12 in. emitter spacing with a flow rate of 0.5 gallon a minute per 100’ of tape buried 1 inch. The experimental area was equipped with WR-32 brass impact sprinklers aluminum arm with 9/64” nozzles with 4.07 gpm at 50 psi (Wade Rain Inc., 2007) for frost protection and crop establishment. These are the most common sprinklers used by growers. The cultivars used were: ‘Strawberry Festival’ and ‘Treasure’. Bare-root strawberry transplants were planted in double rows 12 ft. apart. After transplanting, overhead irrigation was used for 9 hours for the first 14 days to ensure plant establishment.

Treatments

The strawberry field experiment tested a set of 5 treatments with 3 replications, totaling 15 plots (Table 2). Each plot had five planted rows 16 to 24 linear ft. WR-32 brass impact sprinklers altering irrigation system pressure and sprinkler spacing were tested. The pressures under evaluation were 50 and 30 psi, and the sprinkler spacings tested were 48 ft. by 48 ft. and 40 ft. by 40 ft.

Table 2. Treatments evaluated. Field experimental project. Citra, Florida. Fall 2011- Spring 2012.

Treatment	Sprinkler	Pressure (psi)	Spacing (ft.)	Control
50 psi	WR-32	50	48 x 48	Manual
30 psi	WR-32	30	48 x 48	Manual
AC	WR-32	50	48 x 48	Automated
NO	No sprinklers	Non frost protected	NA	None
40*40	WR-32	50	40 x 40	Manual

A system pressure of 50 psi was evaluated using sprinkler spacings of 48 ft. and 40 ft. on center (50 psi and 40*40 treatments correspondingly). The 30 psi system pressure was evaluated using 48 ft. spacing (30 psi treatment). Irrigation for these treatments was activated at 34 ºF using a thermostat directly connected to a valve, mimicking a grower turning on the system at this temperature. Another treatment with 48 ft. spacing was implemented so that frost protection was determined by dew point temperature using wireless temperature sensors (AC treatment). Frost protection continued for all irrigated treatments until the temperature exceeded 34 ºF. The control treatment (NO) did not receive frost protection. The experimental design was a split-plot design with three replications.

Yield

The experiment contained 15 plots. The harvest area (H) for all plots consisted of 12 linear ft. of plants in the middle three planted rows whereas the remaining areas of the plot were considered guard row areas (GR) (Fig. 1).

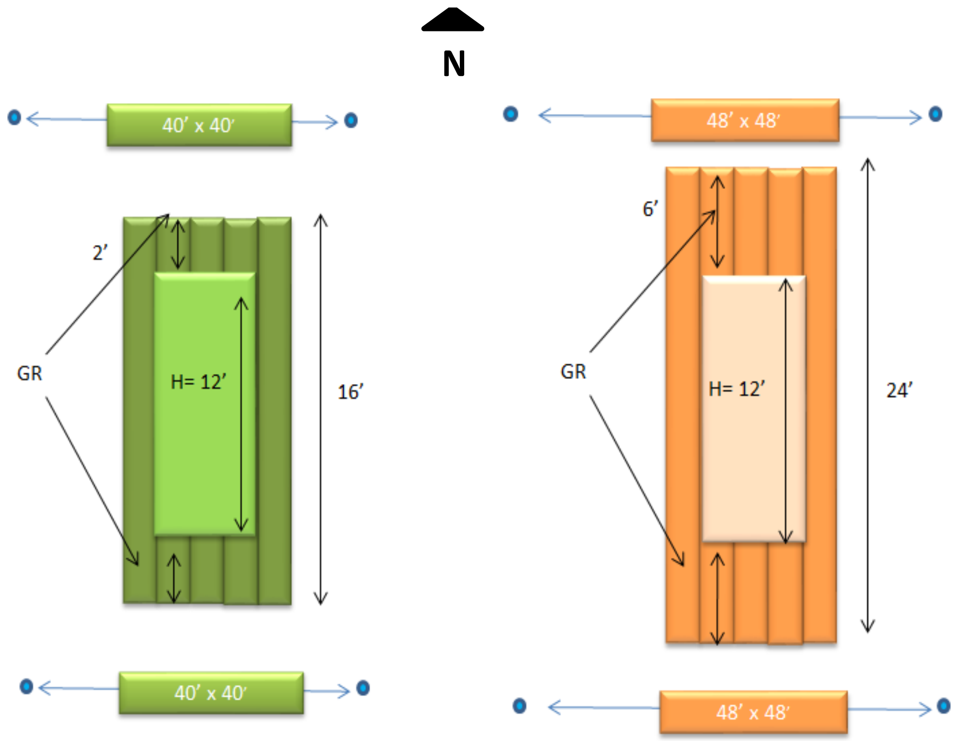

Figure 1. "Cultivated" and "Harvest" areas description.

Temperature

Two different temperature sensors were used to record air temperature in the field: thermocouples and wireless temperature sensors.

1. Thermocouples

The air temperature in the field was recorded using cooper-constantan thermocouples placed within each plot. Temperature was measured below the plant canopy at 1.4 in., above ground, within the plant canopy at 6.3 in., and above the plant canopy at 11.8 in. These thermocouples were connected to 6 dataloggers or "temperature stations". The temperature data recorded was slightly different at each plot. Therefore, the cold events were defined using the data from temperature station 1, this being the station that generally showed the most extreme cold effect (i.e. temperatures below 34 ºF for the longest periods of time).

"Cold events" were defined as periods when temperature station 1 showed temperatures consistently below 34 ºF more than 2 hours. Later in the document, "freeze events" were defined and analyzed according to the "physiological critical temperature" of strawberries, which was found to be 31 ºF. This is the temperature below which damage occurs to the "open blossom" stage of the crop (Table 1).

2. Wireless temperature sensors

The automated controlled treatment (AC) irrigation was activated at a critical temperature derived from Table 1. Air temperature and relative humidity were recorded by wireless sensor devices placed in each treatment plot which were used to calculate an average dew point (DP). Irrigation for cold protection began once the temperature reached a dynamic value, determined using the critical temperature for an open blossom (31 ºF) and the average DP. Table 1 was used to determine the temperature at which irrigation should be turned on. Using this method, the irrigation system was programmed to shut off when temperature exceeded 36 ºF.

Data Analysis

Initial results for cold protection includes minimum leaf temperatures, air temperature, and other climatic data recorded in the strawberry field during the period of November 2011 to March 2012. During every cold event, average minimum air temperature was determined for each plot. Other climatic data such as minimum air temperature at 60 cm, minimum DP temperature and average wind speed was obtained from the Florida Automated Weather Network (FAWN) archived weather data at the station located in Citra, Fl.

Amount of water applied for cold protection

Typically, strawberry growers turn on the irrigation for cold protection about a temperature of 34 ºF approximately. Therefore, for this study, the 50 psi treatment (48 x 48 ft. spacing) with irrigation activated by a thermostat at a temperature below 34 ºF represents a “grower practice” for comparison. The 50 psi treatment was used as a benchmark against which the water savings of all other treatments was measured.

The AC treatment irrigation was activated during 10 cold events while the irrigation for the other treatments; controlled by the thermostat, was activated during 16 events.

The amount of water applied per treatment during the cold events is described in Table 3. The 40*40 treatment resulted in the highest irrigation amount. It used a total of 2,821,255 gallons per acre, representing a 44% extra water application. The AC treatment applied 90,932 gallons less than the 50 psi, representing a 5% of water savings. The 30 psi treatment saved 439,883 gallons during the cold events, this being a 22% of water savings.

Table 3. Amount of water applied during the cold events and percent water savings per treatment (compared to 50 psi treatment). Citra, Fl. Fall 2011- Spring 2012.

Treatment	Pressure (psi)	Irrigation (gal applied)*	Gal/ac	Water savings (gal/acre)	Water Savings (%)
AC	50	296,454	1,868,016	90,932	5
50 psi	50	310,885	1,958,948	-	0
30 psi	30	241,076	1,519,064	439,883	22
NO	-	-	-	1,958,948	100
40*40	50	310,902	2,821,255	-862,307	-44

* Total irrigation (gal) applied on the three plots of the treatment, over all cold events.

Freeze events according to the crop stage critical temperature (30 °F)

The physiological critical temperature was defined as 30 °F, this being the critical temperature below which damage occurs to the "open blossom" stage of the crop (Table 1). Only eight freeze events presented temperatures below physiological stage critical temperature (30 °F). All of them were freeze protected (AC and "grower practice" (thermostat-controlled) irrigation). A comparison between treatments during the critical temperature freeze events, with the 50 psi treatment as the water saving benchmark is described in Table 4. AC used 226,181 gal/acre extra water, or 15% more than the "grower practice". Reducing the pressure to 30 psi resulted in 22% water savings (335,461 gal/acre). The 40*40 treatment increased the water use by 44% applying 657,608 gal/acre more than 50 psi treatment.

Table 4. Amount of water applied during the physiological critical temperature events (<30 ºF) and percentage of water savings per treatment (compared to "grower practice" (50 psi)). Citra, Fl. Fall 2011- Spring 2012.

Treatment	Pressure (psi)	Irrigation (gal applied)	Gal/acre	Water savings (gal/acre)	Water Savings (%)
AC	50	272,980	1,720,102	-226,181	-15
50 psi	50	237,085	1,493,921	-	0
30 psi	30	183,848	1,158,461	335,461	22
NO	0	-	-	1,493,921	100
40*40	50	237,099	2,151,529	-657,608	-44

Strawberry yields

Strawberries were harvested twice per week from December 2011 until March 2012. However, for the results of the statistical analysis yield was weighted in order to have an equal number of days between the harvests. The weighted marketable weight for a total of 23 harvests during the period of December 2011 to March 2012 is shown in Figure 3. The "grower practice" irrigation (thermostat controlled) was triggered for 16 cold events, while automatic control irrigation (AC) was triggered for only 11 cold events. Statistical analysis was performed taking into account the recovery of the treatments after each cold period.

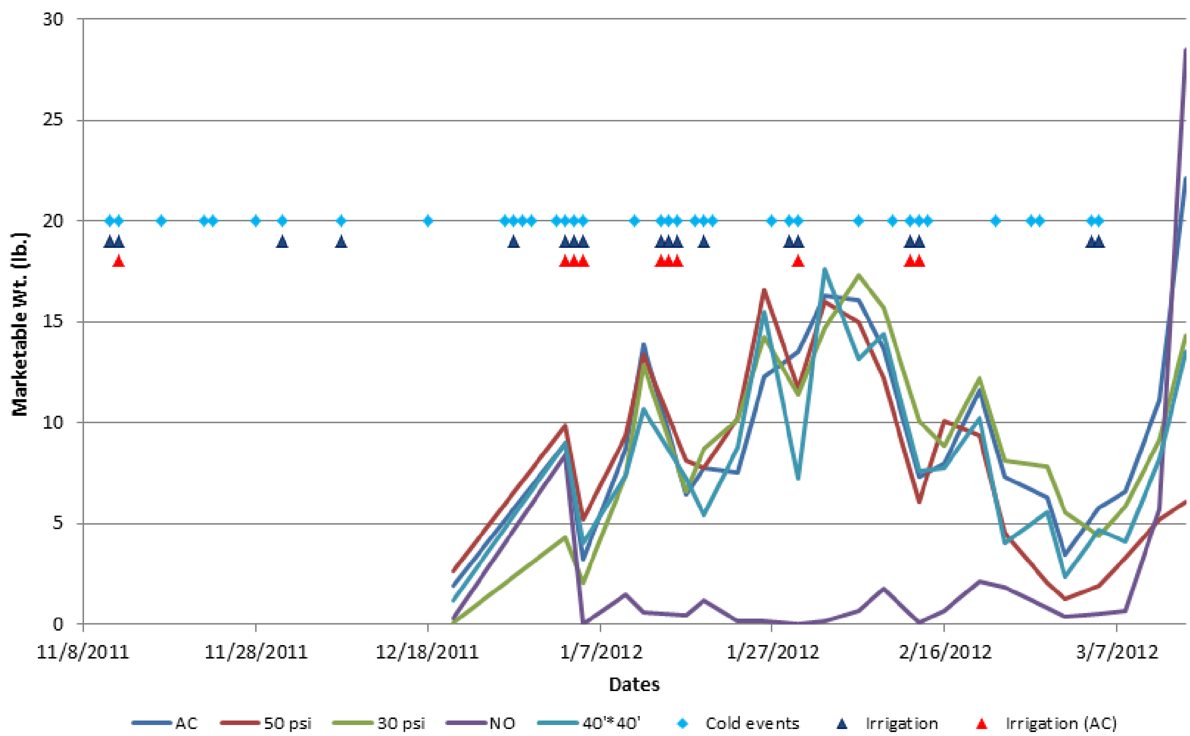

Figure. 3. Weighted marketable weight per treatment (lb.). Irrigation for freeze protection during the cold events. Citra, Fl. Fall 2011 – Spring 2012.

Initial results showed significant yield differences between the irrigated treatments and the control (non-irrigated, NO) (Fig. 3). Yield and volume applied during cold events for each treatment were compared to the 50 psi treatment.

The non-irrigated treatment showed significant differences from the 50 psi treatment. It was affected by the initial cold events and thus produced very low marketable weights during the whole harvesting period. AC and 40*40 both showed only slight differences in yield compared to 50 psi. However, the 30 psi treatment achieved water savings of 22% without a large effect on yield throughout the harvesting period, and even it gave a slightly higher yield at the middle and at the end of the harvest period.

Average yield was analyzed using the Least Square Difference method of Bonferroni (LSD_{Bon} = 0.2310), shown in Table 5. The average yield of the non-irrigated treatment was significantly different from the other treatments for all pairwise comparisons (NO, AC, 50 psi, 30 psi and 40*40) (Table 6).

Table 5. LSD_{Bon} value for comparison of average treatment yield.

Cold Period	TOTAL
t_{Bon} value	3.83
DF MSE	8
MSE (Error 1)	0.00544
# of Contrasts	10
# of Rep	3
LSD_{Bon}	0.2310

The cold events occurring between December 2011 and March 2012 were grouped into a total of 5 recovery periods based on the cold's effect on yield during those periods. This was done in order to evaluate the recovery of the treatments after each cold period. LSD_{Bon} results comparing the NO treatment (control) versus the irrigated treatments (AC, 50 psi, 30 psi and 40*40) are shown in Appendix 1. The non-irrigated treatment mean was 66.4% lower on average during the 5 recovery periods (LSD_{Bon} NO greater than critical LSD_{Bon} for each period).

For the irrigated treatments, significant differences were found only for recovery period 5 (Table 6) when 30 psi treatment showed 50%, 44% and 77% higher yields than 40*40, 50 psi and NO treatments correspondingly during harvest 17, and 74% and 89% higher yields than 50 psi and NO treatments during harvest 18. In contrast, 50 psi obtained the lowest mean yield for the last harvest (February 28th) and it was 74% and 63% significantly lower than 30 psi and 40*40 respectively (Table 7). Irrigated treatments always showed a linear increase in the yield after each cold event, but that was not observed in the control treatment.

Table 6. Average yield LSD_{Bon} results for all pairwise comparisons (NO, AC, 50 psi, 30 psi and 40*40).

Treatment		Diff according to				
	Means (lb.)	30 psi	40*40	50 psi	AC	NO
30 psi	1.39	0.00	-0.15	-0.16	0.05	-1.02*
40*40	1.25		0.00	-0.01	0.20	-0.87*
50 psi	1.23			0.00	0.21	-0.86*
AC	1.45				0.00	-1.07*
NO	0.37					-

(*) Significant differences between treatments.

Table 7. LSD_{Bon} results comparing the non-irrigated treatment (control) vs. the irrigated treatments (AC, 50 psi, 30 psi and 40*40) during recovery period 5.

LSD_{Bon}	0.4810					
Harvest	# 17	Diff according to				
	Average Means (kg.)	30 psi	40*40	50 psi	AC	NO
30 psi	1.22	-	b	b	a	b
40*40	0.61		-	a	a	a
50 psi	0.69			-	a	a
AC	1.10				-	b
NO	0.28					-
	# 18	30 psi	40*40	50 psi	AC	NO
30 psi	1.18	-	a	b	a	b
40*40	0.84		-	b	a	b
50 psi	0.31			-	b	a
AC	0.95				-	b
NO	0.13					-

Different letters denote significant differences between treatments

Table 8 shows the LSD_{Bon} results comparison within irrigated treatments (AC, 50 psi, 30 psi and 40*40) during recovery period 5. Recovery capability from the cold events among the irrigated treatments differs significantly only for recovery period 5. The least recovery was showed by the 50 psi treatment which presented 44% significantly lower yields than 30 psi during harvest 17. During harvest 18, 50 psi obtained 74%, 63% and 67% significantly lower yields than 30 psi 40*40 and AC treatments respectively (Table 8).

Table 8. LSD_{Bon} results comparing the irrigated treatments (AC, 50 psi, 30 psi and 40*40) during cold period 5.

LSD_{Bon}	0.5190				
Harvest	# 17	Diff according to			
Treatment	Average Means (kg)	30 psi	40*40	50 psi	AC
30 psi	1.22		b	b	a
40*40	0.61			a	a
50 psi	0.69				a
AC	1.10				
	# 18	30 psi	40*40	50 psi	AC
30 psi	1.18		a	b	a
40*40	0.84			b	a
50 psi	0.31				b
AC	0.95				

Different letters denote significant differences between treatments

Conclusion

Sprinkler irrigation effectively protected strawberries from cold damage. Initial results showed significant yield differences between the irrigated treatments and the control. Recovery capability from the cold events among the irrigated treatments did not differ significantly. Irrigated treatments always showed a linear increase in the yield after each cold event, but that was not observed in the control treatment. No yield differences between the irrigated treatments (AC, 50 psi, 30 psi and 40*40) were found; however, water usage differences were found within them. The 30 psi treatment achieved water savings of 22%, which could reduce water use by 439,883 gallons per acre of crop per season without affecting yield. Therefore, a total of 25 billion gallons of water could be saved considering the 57,470 acres of strawberries harvested in Florida in 2011. Further investigation will be done this year to repeat the experiment.

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Appendix

Appendix 1. LSD_{Bon} results comparing the non-irrigated treatment (control) vs. the irrigated treatments (AC, 50 psi,30 psi and 40*40).

Cold Period	1	2	3	4	5
t_{Bon} value	2.74	2.74	3.04	2.74	3.04
DF MSE	20	20	10	20	10
MSE (Error 2)	0.1235	0.0547	0.1861	0.08753	0.03755
# Contrasts	4	4	4	4	4
# Rep	3	3	3	3	3
LSD_{Bon} within each cold period	0.7862	0.5232	1.0708	0.6619	0.4810

Note: LSD_{Bon} was calculated using Balanced ANOVA for average yield.

Appendix 2. LSD_{Bon} results comparing the irrigated treatments (AC, 50 psi, 30 psi and 40*40).

Cold period	1	2	3	4	5
tBon value	2.93	2.93	3.28	2.93	3.28
DF MSE	20	20	10	20	10
MSE (Error 2)	0.124	0.055	0.186	0.088	0.038
# of Contrasts	6	6	6	6	6
# Repetitions	3	3	3	3	3
LSD_{Bon} per Time	0.8407	0.5595	1.1553	0.7078	0.5190

Note: LSD_{Bon} was calculated using Balanced ANOVA for average yield.

Seasonal irrigation requirements and irrigation scheduling of soybeans

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Abstract.

While rainfall in Mississippi is usually abundant, the temporal distribution and amount are unpredictable. Soybean producers in Mississippi are increasingly incorporating irrigation practices into their production systems, and are interested in developing tools and strategies to assist in making irrigation decisions and maintaining optimal plant-growth conditions.

A three-year study was begun to evaluate water-use requirements of soybean, evaluate irrigation scheduling methods, and examine impacts of irrigation management on soybean yield and quality. The study was conducted in a 15-ac field under a center-pivot, overhead-sprinkler irrigation system equipped with variable-rate application control capability. Irrigation treatments consisted of varying depths of irrigation water applied, based on evaporative demand (or evapotranspiration, ET), ranging from 0 to 125% of ET.

Two versions of the Arkansas Irrigation Scheduler, and a spreadsheet scheduling model, were tested to determine the timing of irrigations, and four irrigation applications were made during the season. Soil-moisture sensors installed in each plot indicated that soil-water reserves were sufficient throughout the growing season and that the soybean plants under all irrigation treatments may have been exposed to minimal water stress. Average treatment yields ranged from a minimum of 66.9 bu/ac for the non-irrigated treatments to a maximum of 77.8 bu/ac for the 100% ET treatment. An analysis of variance test showed no significant differences ($P = 0.256$) between treatments, indicating that the amount of irrigation water applied did not significantly affect yield. This was most likely a result of the rainfall patterns observed, in which sufficient rainfall occurred at timely intervals.

Keywords. soybean, center pivot, variable rate, soil moisture, irrigation scheduling

Introduction

Rainfall in Mississippi is abundant, but for Mississippi soybean producers, rainfall occurring during the crop-production season is of prime importance. Because the temporal distribution of rainfall is unpredictable and may not be sufficient or timely for satisfying crop-water demands and enabling optimal growth and yield production, producers are increasingly incorporating irrigation practices into their production systems. Irrigation involves the proper timing and amount of water application to satisfy crop-water needs. Proper timing is necessary to avoid drought, or water-stress, conditions, and to avoid overly wet or prolonged periods of waterlogged conditions, both of which can negatively impact plant health and yield. Proper amount of water application is necessary to adequately replenish soil-water resources so that plants have adequate access for continued growth, while minimizing losses through runoff or deep percolation.

In order to enable efficient irrigations and make best use of water resources, the water-use requirements of soybean need to be determined. Water-use is a function of environmental demand, and soybean-plant systems use water through the combined processes of transpiration and evaporation in response to the climatic conditions in which they grow. Since environmental conditions are site-specific, monitoring of climatic conditions and soybean growth, water-use, and yield under local conditions is necessary to provide this information to Mississippi producers.

While irrigation is an important component of a producer's farm management activities, its importance in optimizing plant growth, yield, and quality can be overlooked or neglected. Irrigation can be a labor-intensive and time-consuming activity, and producers often try to simplify the process to better fit in with other farm operations, rather than performing the irrigation when and how it is most effective. Producers are interested in developing tools and strategies to assist in making irrigation decisions and maintaining optimal plant-growth conditions. Since water plays a major role in plant growth processes, metabolic reactions, fruit formation and retention, and disease infection, its proper application can have a significant effect on crop yield and quality.

Objectives

The objectives of this study were to (1) evaluate irrigation scheduling methods, (2) evaluate water-use requirements, (3) monitor soil-moisture status to detect moisture stress, and (4) examine impacts of irrigation management on soybean yield.

Materials and Methods

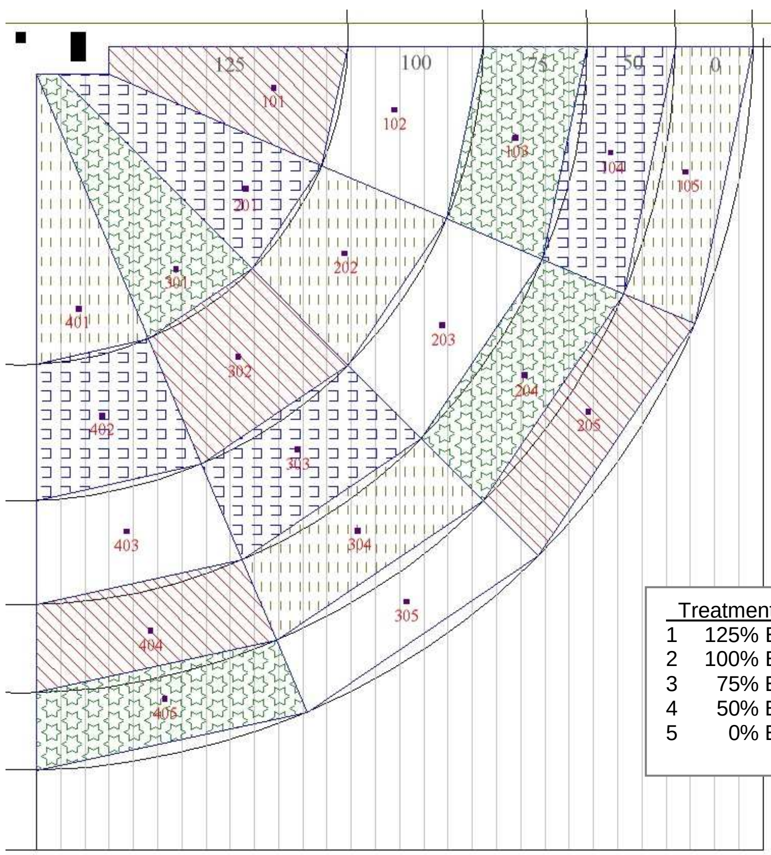
The study was conducted in 2012 at the USDA ARS's Jamie Whitten Delta States Research Center at Stoneville, MS (latitude 33.48 N, longitude 90.98 W, elevation 138 ft). A 15-ac field under a center-pivot, overhead-sprinkler system was planted on 24 April 2012 to soybean, Pioneer P94Y70, with a 38-in row spacing at a density of 120000 seed/ac.

Plots were established under a one-quarter section of the center pivot's circle in a completely randomized block design. Five irrigation treatments were defined, with four replications of each treatment, resulting in a total of 20 plots. Treatments consisted of five irrigation-application levels; 0% (non-irrigated), 50%, 75%, 100%, and 125% of ET (evapotranspiration). The area outside the center pivot's circle was not irrigated. Plot layouts and treatments are shown in Figure 1.

The irrigation system consisted of a Valley model 8000 center-pivot equipped with Valley's Variable Rate Irrigation (VRI) Zone Control (Valmont Irrigation, Valley, NE). The center-pivot system included four spans, with a total length of 766 ft, and 86 sprinklers. The VRI system enabled sprinkler output to be controlled via electric solenoid valves. The sprinklers were each equipped with an electric solenoid valve, and were grouped into 10 zones. Each zone was designed to cover the same surface area as the pivot travelled around the center, with the number of sprinklers in each zone varying from 5 to 27. Each zone could be programmed to operate the solenoid valves with duty cycles varying from 0% (continuously closed) to 100% (continuously open) in 10% increments to vary the amount of water applied. As the pivot travelled around the field, zone settings could be independently controlled every 2 degrees.

Irrigation timing was determined based on evaporative demand (or evapotranspiration, ET) and a water-balance irrigation scheduling method. Daily reference ET (ET_o) was first estimated using the standardized weather-based FAO-56 evapotranspiration method (Allen et al., 1998). Weather data were obtained from an automated weather station at Mississippi State University's Delta Research and Extension Center experiment station at Stoneville, MS. Daily ET_o was calculated using the weather data, then adjusted using a crop coefficient to estimated daily crop ET (ET_c) for soybean. ET_c, rainfall, and irrigation application amounts were then input to an irrigation scheduling program which tracked daily water use and the soil-water deficit. When the deficit reached a preset threshold, an irrigation was scheduled for the following day.

Soil-moisture sensors were installed in each plot to monitor soil-water resources and soil-water extraction, and to monitor the level of water stress. Water-potential sensors (Watermark Model



Treatment		VRI setting	Plots
1	125% ET	100%	101, 205, 302, 404
2	100% ET	80%	102, 203, 305, 403
3	75% ET	60%	103, 204, 301, 405
4	50% ET	40%	104, 201, 303, 402
5	0% ET	0%	105, 202, 304, 401

Figure 1. Plot layout showing irrigation application treatments.

200SS, Irrometer Company, Riverside, CA) were installed at 6, 12, and 24 in below the soil surface. Sensor measurements were collected with an inexpensive open-source datalogging device (Fisher and Gould, 2012) at 1-hr intervals and stored to a memory card. During periodic site visits, data were downloaded to a tablet computer for later analysis.

During soil-moisture sensor installation, GPS coordinates of each sensor location were recorded, and a "virtual plot" was constructed around the sensor location. The virtual plot consisted of a box 16 rows wide and 50 ft in length centered about the sensor location. The GPS coordinates of the four corners of the box were recorded, and would be used following harvest for yield estimation.

At the end of the season, the field was harvested with a mechanized grain harvester. Yield data was collected and recorded with a GPS-based yield monitor, which measured yield continuously as the harvester travelled across the field. The yield monitor was calibrated by weighing several harvester-loads of soybean in a loadcell-equipped grain cart and entering actual weights into the yield monitor.

Results

The 2012 growing season was warm with dry periods in the Mississippi Delta region. While there were some hot periods during the growing season, monthly average maximum air temperatures were near long-term normal values for June, July, and August. Rainfall during the growing season totaled 17.9 in, approximately 2 in higher than normal, but the majority of the rainfall occurred during three storm events in late May-early June, late June, and late August. Between rain events, little to no rainfall occurred for periods of three to four weeks.

Daily reference ET values ranged between 0.10 and 0.27 in/day during the season, with a seasonal average of 0.19 in/day. Based on a crop coefficient function for soybean with values of 0.2 early in the season, 1.00 during the peak season, and 0.5 at harvest, crop ET ranged between 0.02 and 0.25 in/day. ET_o estimates, maximum air temperature, and rainfall measurements are shown in Figure 2.

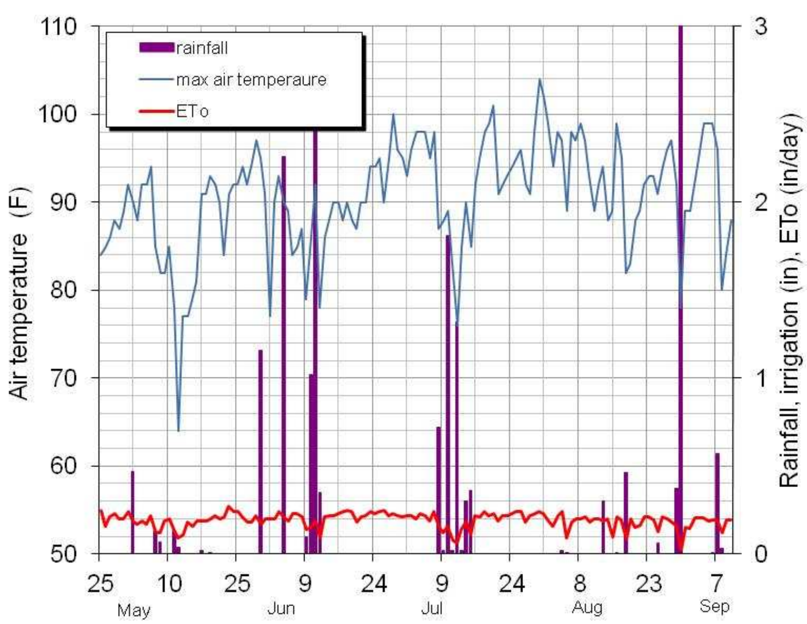


Figure 2. Daily reference ET, air temperature, and rainfall.

Irrigation scheduling

Two water-balance irrigation scheduling models were tested to examine differences in scheduling recommendations. One model, the Arkansas Irrigation Scheduler (Cahoon et al., 1990; Vories et al., 2005), was a stand-alone computer program that required minimal data input to set up (type of crop, irrigation system, planting and emergence dates) and use (daily maximum air temperature or reference ET, rainfall, and irrigation). The Arkansas Irrigation Scheduler, when first written, used air temperature and an empirical correlation to estimate ET_o. The program was later updated to allow the user to directly enter ET_o values, calculated using a reference-ET method such as the FAO-56 Penman-Monteith method, to potentially provide more accurate crop ET estimates and improve the performance of the water-balance model. The program used a built-in crop coefficient function to adjust ET_o and estimate ET_c of soybean.

The second model consisted of a simplified water-balance constructed in a computer spreadsheet (Fisher and Pringle, 2010). ET_o was estimated by an empirical equation developed by Turc (1961), which used maximum air temperature and solar radiation, which was then adjusted with a crop coefficient function to estimate ET_c. A daily soil-water deficit was then calculated by subtracting ET_c and adding rainfall and irrigation amounts to the previous day's deficit.

In making irrigation scheduling decisions during the season, the Arkansas Irrigation Scheduler with FAO-56 ET_o input was used. A deficit of 2.00 in was selected as the threshold for irrigation initiation. When the model's soil-water deficit reached this amount, an irrigation was scheduled for the following day.

Resulting soil-water deficit estimates for the Arkansas Irrigation Scheduler and the spreadsheet model are shown in Figure 3 for the 100% ET treatment. For the Arkansas Irrigation Scheduler, the soil-water deficit increased at a much faster rate when maximum air temperature was used (Figure 3b). This indicates that daily ET_o values generated by the program were higher than those estimated using the FAO-56 method (Figure 3a). Using the temperature-based version, an extra irrigation would have been signaled in late May, and the irrigation on June 29th would have been triggered several days earlier. The rainfall in early July would have been insufficient to replenish soil-water reserves, with an irrigation called for soon after that rainfall event, and excessive soil-water deficit occurring in the latter part of the season. The spreadsheet model (Figure 3c) agreed well with the Arkansas Irrigation Scheduler with ET_o input. Using a spreadsheet had an advantage of providing a graphical output, rather than the simple text output generated by the Arkansas Irrigation Scheduler, allowing for easier interpretation and observance of trends in the soil-water deficit information.

During the season, a total of four irrigation applications were made. The variable-rate center-pivot irrigation system was programmed to apply five application-rate treatments, shown in Figure 1. Based on the design capacity of the center pivot, the 100% treatment was programmed to apply 1.00 in of water during an irrigation, with the other treatments applying an amount proportional to their treatment percentages (125% = 1.25 in, 75% = 0.75 in, 50% = 0.50 in, and 0% = 0 in, or not irrigated). During each irrigation, as the variable-rate system traveled across the field, solenoid valves cycled open and closed to allow the proper amount of water to be applied to each plot.

Soil moisture measurements

Soil-moisture measurements were collected at three depths (6, 12, and 24 in below the soil surface) at the center of each plot at 1-hr intervals throughout the season. Measurements from the four replicates of each treatment were averaged for each depth, and are shown in Figure 4. For each

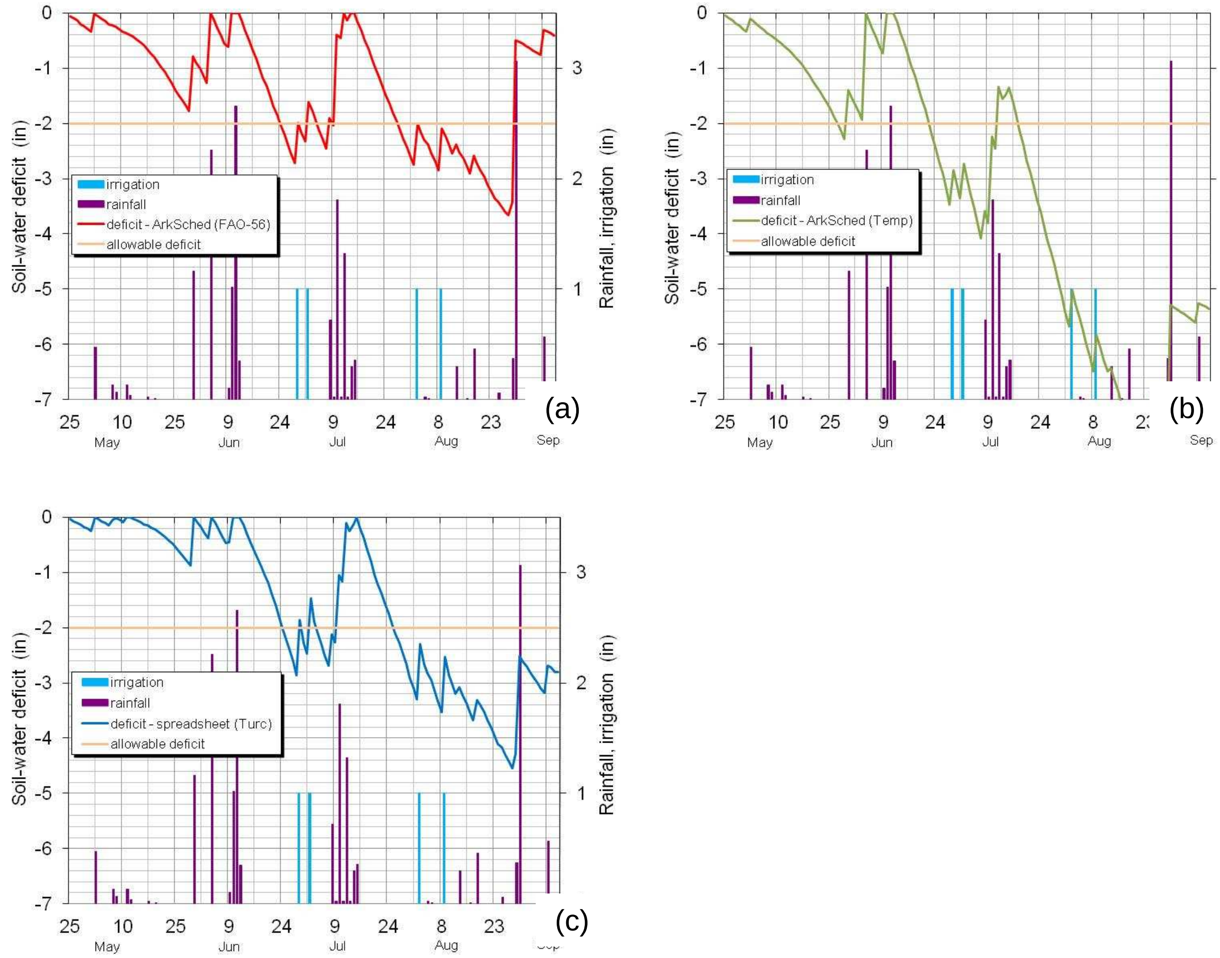


Figure 3. Irrigation schedules from the (a) Arkansas Irrigation Scheduler with ET_o input, (b) Arkansas Irrigation Scheduler with temperature input, and (c) spreadsheet model.

treatment, soil-water potentials remained above the threshold level of -60 kPa for much of the season, suggesting that the plants were not exposed to significant water stress.

The infrequent but heavy rainfall events provided moisture which satisfied crop-water demands for several weeks, minimizing the need for supplemental irrigation. The timing of the first irrigation, signaled by the irrigation scheduling model in late June, agrees fairly well with the soil-moisture sensor data for the 100% ET treatment (Figure 4b). In order to apply 2 in of water, the center pivot was run over the field in one direction, then a few days later in the reverse direction. In early August, the scheduling model called for an additional irrigation, but moisture-sensor data suggest that the plants still had access to sufficient soil-water reserves, and that the irrigation could have waited. The less-irrigated treatments also appeared to be under little stress, and the last two irrigations may not have been necessary.

Yield

On 10 September 2012, the field was harvested, and a yield map was generated from data collected with the GPS-equipped yield monitor, shown in Figure 5. The yield map shows the location of the

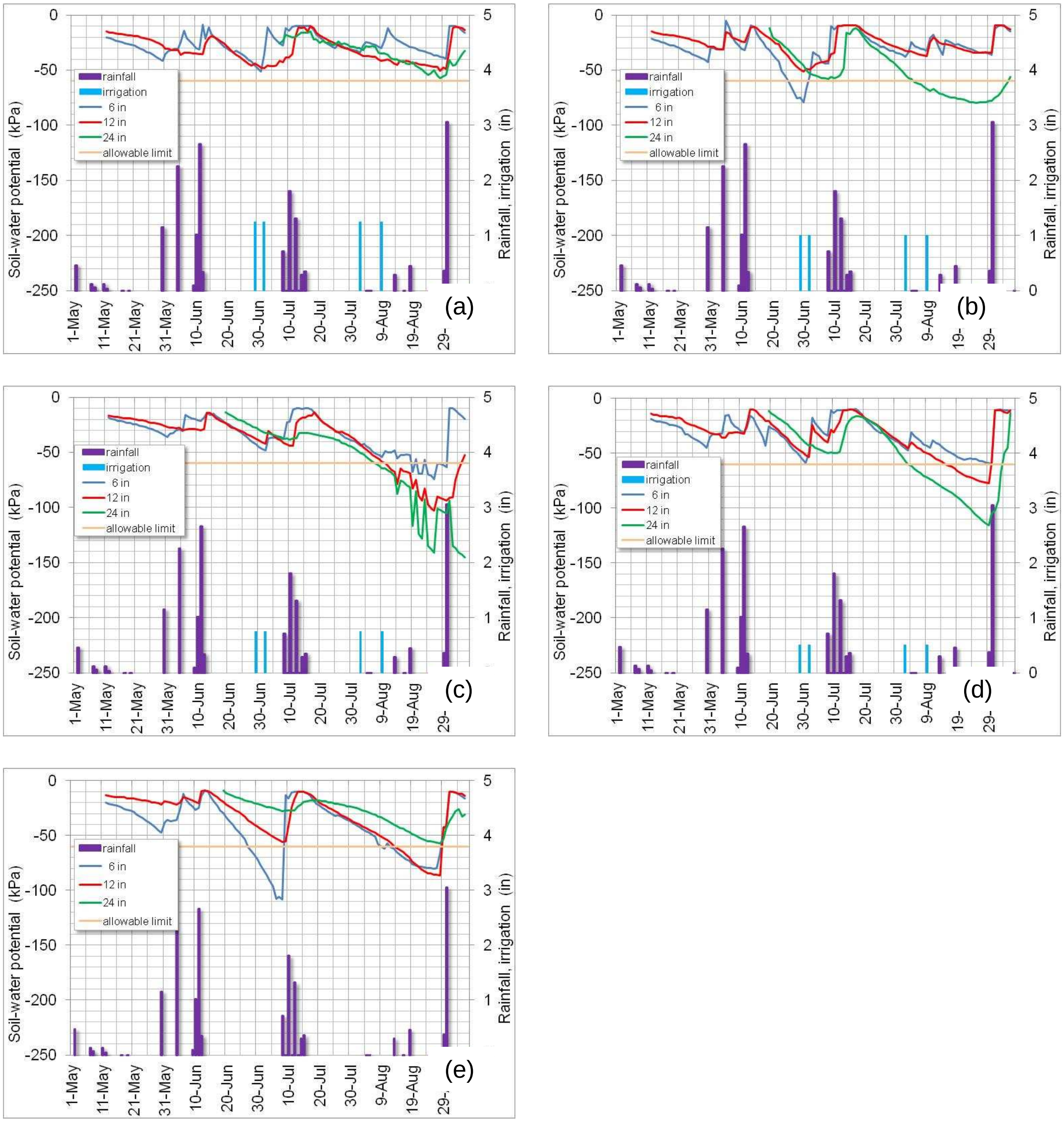


Figure 4. Soil-moisture sensor measurements under each irrigation application treatment: (a) 125%, (b) 100%, (c) 75%, (d) 50%, and (e) 0% (non-irrigated).

pivot's center in the upper-left corner, and the circular sweep of the 5 variable application-rate zones under the center pivot. Extending radially from the pivot's center, three alleyways can be seen, which were made by mowing the soybean plants to allow easier movement within the field during the season and enable visits to each sensor location. Yields generally ranged from around 50-60 bu/ac in the non-irrigated sections to above 90 bu/ac in irrigated areas, with a whole-field average of 67 bu/ac.

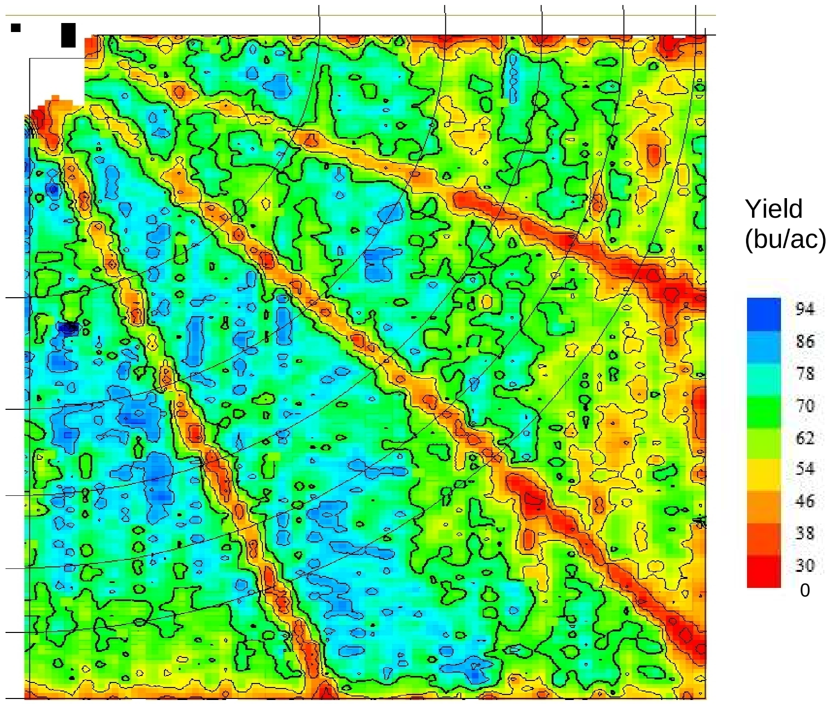


Figure 5. Yield map.

Average yields for each plot were estimated from the virtual plots centered at the moisture-sensor locations within each treatment plot. GPS coordinates of each yield-data point were used to identify those points which were inside the virtual plots. The yield-data points within each virtual plot were then averaged to obtain a yield estimate for each irrigation treatment and replicate. Yields for each plot, and average treatment yields are shown in Figure 6. Average treatment yields ranged from a

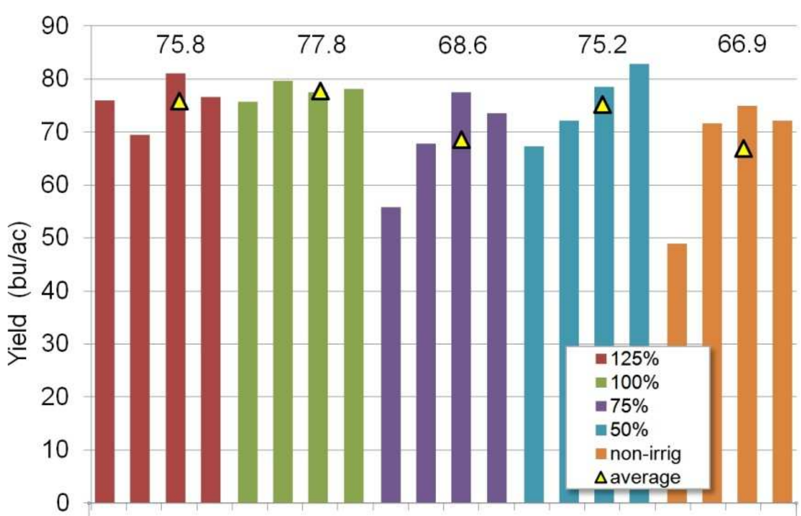


Figure 6. Individual plot and average treatment yields.

minimum of 66.9 bu/ac for the non-irrigated treatments to a maximum of 77.8 bu/ac for the 100% ET treatment.

An analysis of variance test showed no significant differences ($P = 0.256$) between treatments, indicating that the amount of irrigation water applied did not significantly affect yield. This was most likely a result of the rainfall patterns observed, in which sufficient rainfall occurred at timely intervals, and supplemental irrigation may not have been needed. This is evidenced by soil-moisture sensor measurements which suggest that there was little moisture stress observed in the non-irrigated plots.

Conclusion

Soybean producers in Mississippi are increasingly incorporating irrigation practices into their production systems, and are interested in developing tools and strategies to assist in making irrigation decisions and maintaining optimal plant-growth conditions. A three-year study was begun to evaluate water-use requirements of soybean, evaluate irrigation scheduling methods, and examine impacts of irrigation management on soybean yield and quality.

Two versions of the Arkansas Irrigation Scheduler, one using air temperature to estimate ET_o and the other using FAO-56 ET_o directly as input, were tested. The temperature-based version appeared to greatly overestimate crop ET, and recommend irrigations earlier than needed. A simplified spreadsheet water-balance model was also tested, and agreed well with the ET_o-input Arkansas Irrigation Scheduler predictions.

Irrigation treatments were applied four times in response to the Arkansas Irrigation Scheduler output. The variable-rate irrigation system applied water to the randomly distributed treatment plots in amounts ranging from 0 to 125% of ET.

Soil-moisture sensors installed in each plot indicated that soil-water reserves were sufficient throughout the growing season and that the soybean plants under all irrigation treatments may have been exposed to minimal water stress.

A yield map of the field was generated and used to estimate plot and treatment yields. Average treatment yields ranged from a minimum of 66.9 bu/ac for the non-irrigated treatments to a maximum of 77.8 bu/ac for the 100% ET treatment. An analysis of variance test showed no significant differences ($P = 0.256$) between treatments, indicating that the amount of irrigation water applied did not significantly affect yield. This was most likely a result of the rainfall patterns during the season, in which sufficient rainfall occurred at timely intervals.

Results discussed were obtained during the first year of a three-year study. In the following years, the study will be repeated, with additional testing of scheduling models, and additional agronomic measurements collected to better characterize plant and environmental conditions.

Acknowledgements

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Disclaimer

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Investigating the Interaction of Irrigation, Surfactant and Fertilizer Rates on Nitrate and Chlorophyll Contents of Tomato Leaves

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Abstract: *Tomato is one of the most important vegetables grown in the United States. Due to continuous rise in the cost of fertilizers and irrigation water crisis, there is a need to continuously find ways for efficient use of fertilizers and irrigation water, without affecting the quality and quantity of the tomatoes. Current approaches involve utilizing products such as soil surfactants which can potentially enhance water and nutrient uptake by plants, and thereby optimize overall crop productivity. The objective of this study was to evaluate the influence of surfactant, Nitrogen (N) fertilizer and irrigation rates on the nitrate concentration and chlorophyll content of tomato leaves. The study was conducted on a sandy loam soil, as a split-split plot experiment, with irrigation (high, medium and low) as the main factor, and surfactant (with and without) and fertilizer rates (100, 150 and 200 lbs N/acre) as secondary factors. Leaf petioles were analyzed for nitrate concentrations at 1" diameter of fruit stage (first ripe stage) and at harvest, with weekly chlorophyll contents in leaves determined using a SPAD 502 Plus Chlorophyll Meter. At first ripe stage, fertilizer rates had a significant effect (P = 0.02) on leaf tissue nitrate content, with rates of 150 and 200 lbs N/acre resulting in the highest levels for all the irrigation and surfactant treatments. At harvest, mean petiole nitrate level was highest in plants receiving 200 lbs N/acre, and there was also was an interaction effect of the three treatments at the P=0.10 significance level. Overall, there was a slight decrease in the chlorophyll contents in leaves as the tomatoes progressed from immature green stage to harvest. However, at the harvest stage there was no difference in chlorophyll content for plants grown on soil treated with or without surfactants. These initial findings concur with our earlier studies with turfgrass which indicated that the addition of soil surfactants can potentially enhance vegetative plant growth.***

Keywords. *Surfactant, Water use efficiency, Nitrogen use efficiency, Nitrates in petiole, Chlorophyll, and SPAD 502 Plus meter.*

NOTE: This work represents the first year of our ongoing study to evaluate the effect of surfactant use on water and nitrogen use efficiency in vegetable production. A second trial was conducted during Summer 2012 and complete findings should be available by June 2013.

Introduction

The United States (U.S.) is the second largest producer of tomatoes worldwide and California is the leading producer of all tomatoes in the U.S. Most of the tomato production in California is located in San Joaquin Valley and Sacramento Valley. Input costs for agriculture continue to rise due to cost of fertilizers, fungicides and insecticides. Efficient use of water is important in the areas of irrigation water crisis. However, soil Water repellency causes non- uniform moisture levels in the soil due to which plants may deprive of consistent water supply and may also result in non-uniform distribution of soil applied fertilizers, fungicides and insecticides. To date, soil surfactants have been successfully used for the management of non-uniform moisture distribution in turf grasses. However, the application of surfactants to enhance vegetable production is a relatively new practice and most of positive effects reported by growers have been anecdotal, and so there is a need to scientifically assess the impact of surfactant usage in vegetables, such as tomatoes, production.

The objective of this study was to evaluate the influence of surfactant, Nitrogen (N) fertilizer and irrigation rates on the nitrate concentration and chlorophyll content of tomato leaves.

Materials and Methods

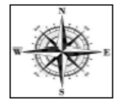
The study was conducted at California State University- Fresno (Fresno State). During summer 2011, tomatoes (*Lycopersicon esculentum* Miller) *cv* Quali-T 23 were grown on sandy loam soil, at the Center for Irrigation Technology (CIT) research plots. Quali- T 23 is a fresh market beefsteak tomato variety, which is a determinate and medium-late maturity type. Plants were hand transplanted on June 10th 2011 with a spacing of 12" between each plant. Twenty seventy tomato beds (5 feet wide x 150 feet long) were used in a split-split plot experimental design comprising of eighteen treatments replicated three times (Figure 1) as follows:

Main plot treatment: Three irrigation rates based on meeting 100% (I1), 80% (I2), 60% (I3) of total crop evapotranspiration (ETc). A manifold with three irrigation lines for the three irrigation rates controlled by electronic valves with an automated data logger system was used. An electronic meter was used to calculate the amount of water added to each irrigation treatment. Water was applied via a subsurface drip irrigation system buried at a depth of 6 inches;

Sub-plot treatment: Plots were treated either with or without surfactant, with S1 and S2 representing whether plots received no surfactant and surfactant at 1 gallons/acre, respectively. For the S2 treated beds, the surfactant was applied three times during the growing season at rates of 0.5 gallons/acre prior to planting, and then two more 0.25 gallons/acre applications at one and two weeks after transplanting. The surfactant was applied using a portable CO_2 spray system by mixing the product with two gallons of water per each half of the bed (75 feet). For the S1 treatment beds, two gallons of water without surfactant was sprayed whenever the S2 treated beds received the surfactant (Figure 2);

Sub-sub plot treatment: Urea Ammonium Nitrate (UAN 32) fertilizer was applied six times over the growing season to achieve total N rates of 100 lbs N/acre (F1), 150 lbs N/acre (F2) and 200 lbs N /acre (F3).

Plot Layout for Aquatrols 2011 Project at CIT



<<-----Barstow avenue------->>

Block 3			Block 2			Block1		
I2	I3	I1	I1	I3	I2	I3	I2	I1
(49) S1F2	(43) S2F1	(37) S1F2	(31) S2F1	(25) S2F1	(19) S2F2	(13) S2F1	(7) S1F2	(1)S1F1
(50) S1F3	(44) S2F3	(38) S1F1	(32) S2F2	(26) S2F3	(20) S2F3	(14) S2F2	(8) S1F1	(2) S1F2
(51) S1F1	(45) S2F2	(39) S1F3	(33) S2F3	(27) S2F2	(21) S2F1	(15) S2F3	(9) S1F3	(3) S1F3
(52) S2F3	(46) S1F1	(40) S2F3	(34) S1F3	(28) S1F2	(22) S1F3	(16) S1F3	(10) S2F2	(4) S2F1
(53) S2F1	(47) S1F2	(41) S2F1	(35) S1F2	(29) S1F3	(23) S1F1	(17) S1F2	(11) S2F1	(5) S2F2
(54) S2F2	(48) S1F3	(42) S2F2	(36) S1F1	(30) S1F1	(24) S1F2	(18) S1F1	(12) S2F3	(6) S2F3
Beds 25-27	Beds 22-24	Beds 19-21	Beds 16-18	Beds 13-15	Beds 10-12	Beds 7-9	Beds 4-6	Beds 1-3

LEGEND	Irrigation	% ET		Surfactant	gal/acre		Fertilizer	lbs N/acre
	I1	100		S1	0		F1	100
	I2	80		S2	1		F2	150
	I3	60					F3	200

Numbers 1 to 54 in ( ) represent the sub plots, which are 3 beds x 25 feet long = 3 beds x 5'/bed x 25' = 375 sq. ft .

Figure 1: Experimental design showing irrigation (I1, I2 and I3), surfactant (S1, S2) and fertilizer rates (F1, F2 and F3).

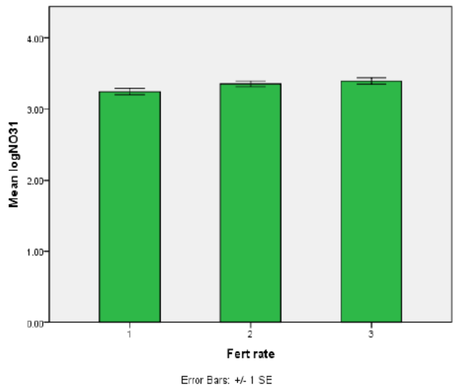
Figure 2: Photos showing the surfactant application (*left*), transplanting tomatoes (*middle)* and fertilizer application (*right*).

Leaf tissue analysis for nitrate was done at 1" diameter of fruit (first ripe stage) and at final harvest stage (red ripe stage). A Konica Minolta SPAD-502® leaf chlorophyll meter was used five times during the growing season to assess the chlorophyll content in the leaves. Four different leaves were used to get an average SPAD reading in each plot during each event.

Data collected was subjected to analyses of variance using the general linear model option in the SPSS® software (SPSS, 2010).

Preliminary Results

Figures 3 to 8 depict the effect of fertilizer and surfactants on the leaf nitrate levels for tomatoes irrigated at the three rates to satisfy 100% (I1), 80% (I2) and 60% (I3) of ETc. The interactive impact of surfactant and fertilizer on these nitrate levels are shown in Figures 9 and 10. Generally, at first ripe stage, fertilizer rates had a significant effect (P=0.02) on leaf tissue NO_3-N concentration, with the leaves from tomatoes receiving 150 and 200 lbs N/acre having the highest NO_3-N levels. At harvest, mean petiole NO_3- N level was highest in plants receiving 200 lbs N/acre. At the 10% probability level (P=0.10), there was a significant interaction, with plants receiving surfactants, and fertilized with 150 & 200 lbs N/acre and irrigated at the 80% and 100% ET having relatively higher nitrate levels than those at 60% ET irrigation rates.



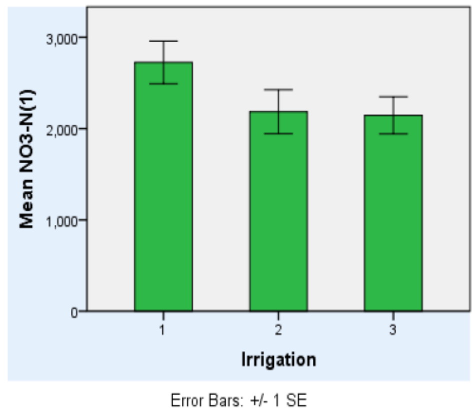
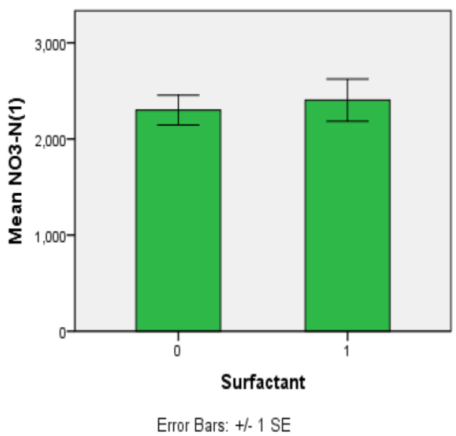


Figure 3: Fertilizer effect at first ripe stage.

Figure 4: Irrigation effect at first ripe stage.



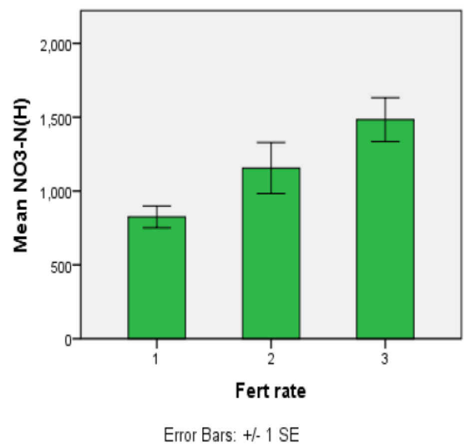
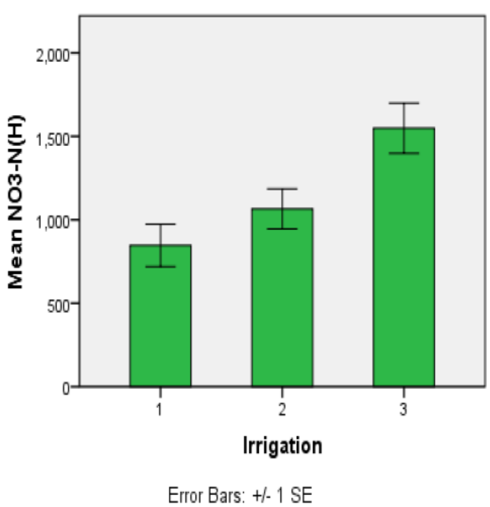


Figure 5: Surfactant effect at first ripe stage.

Figure 6: Fertilizer effect at final harvest stage.



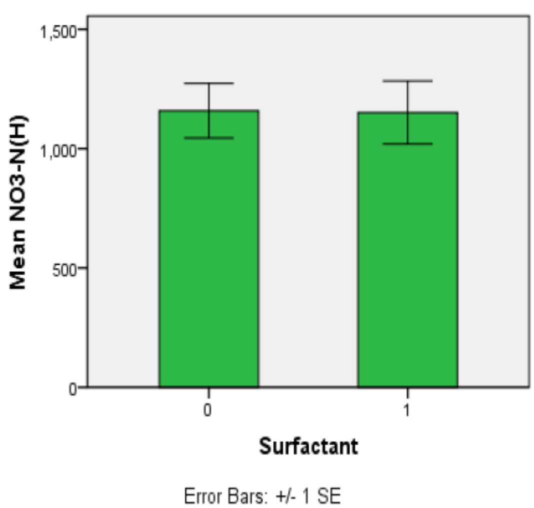


Figure 7: Irrigation effect at final harvest stage.

Figure 8: Surfactant effect at final harvest stage.

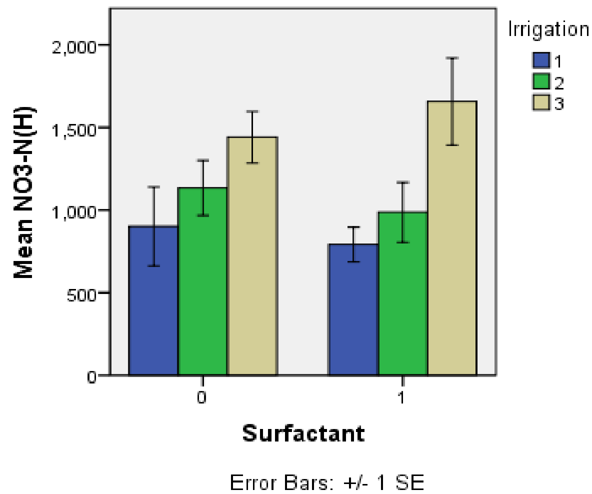


Figure 9: Surfactant and Irrigation interaction at final harvest stage.

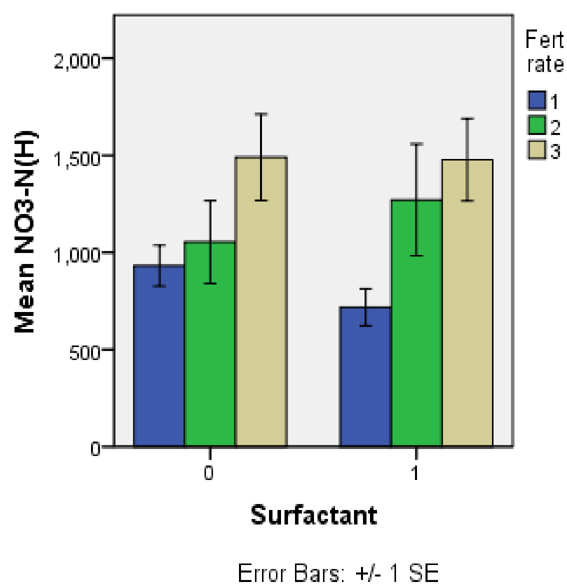


Figure 10: Surfactant and Fertilizer interaction at final harvest stage.

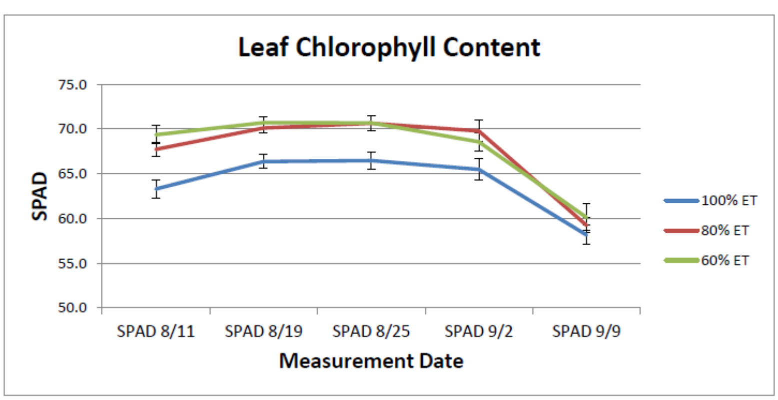


Figure 11: Average SPAD reading for three irrigation rates for five weeks prior to harvest date.

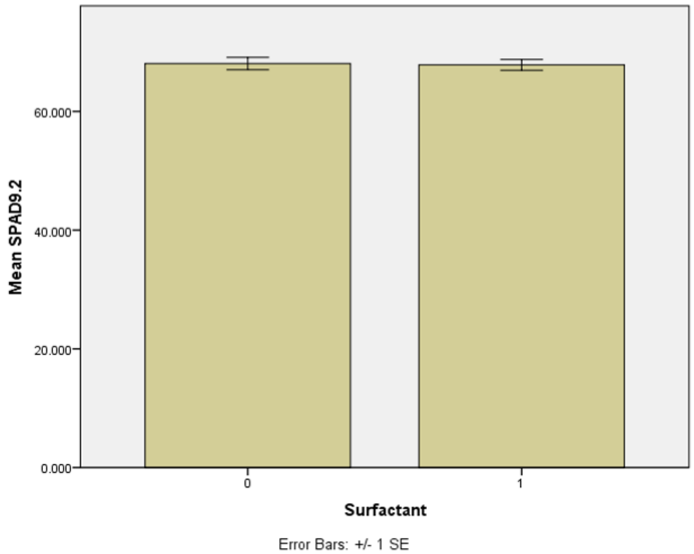


Figure 12: Average SPAD reading at harvest for plots treated with and without surfactants.

Trends in leaf chlorophyll contents measured with th SPAD meter are depicted in Figures 11 and 12. Overall, there was a slight decrease in the chlorophyll contents in leaves as the tomatoes progressed from immature green to full red stage (harvest). At first ripe stage, irrigation rates had a significant effect (P = 0.06) on leaf chlorophyll content. At harvest, there was no significant difference in the chlorophyll content due any of the three factors investigated in this study.

Concluding Remarks

The findings summarized below represent those obtained from the first year of our ongoing study to evaluate effect of surfactant use on water and nitrogen use efficiency in vegetable production. A second trial was conducted during Summer 2012 and complete findings should be available by June 2013.

- At first ripe stage, fertilizer rates had a significant effect (P = 0.02) on leaf tissue nitrate content, with rates of 150 and 200 lbs N/acre resulting in the highest levels for all the irrigation and surfactant treatments.
- At harvest, mean petiole nitrate level was highest in plants receiving 200 lbs N/acre and there was an interaction effect of the three treatments, at the 90% probability level (P=0.10), which resulted in plants grown in soils receiving surfactants, fertilized with 150 and 200 lbs N/ acre, and irrigated at the medium and high rates, having relatively higher nitrate levels than those at the lowest (60% ET) irrigation rates.
- Overall, there was a slight decrease in the chlorophyll contents in leaves as the tomatoes progressed from immature green to full red stage (harvest).
- At first ripe stage, irrigation rates had a significant effect, at the P = 0.06 level, on leaf chlorophyll content. However, at harvest, there was no significant difference in the chlorophyll content due any of the three factors investigated in this study.
- It is noteworthy that unlike other studies reported in the literature, the chlorophyll contents measured with the SPAD meter in this study did not show any positive correlation with the nitrate concentrations determined in leaf petioles.

- These initial findings concur with our earlier studies with turfgrass which indicated that the addition of soil surfactants can potentially enhance vegetative plant growth.
- In future studies, we intend to investigate the correlation between chlorophyll readings and total nitrogen content of the leaves.
- Data from a second round of the experiment conducted in summer 2012 is currently being analyzed.

Acknowledgements

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Drip Irrigation for Sustaining Irrigated Agriculture in Punjab, Pakistan: Issues and Strategy

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Abstract. *Pakistan is one of the world's most arid countries with an average annual rainfall of 240 mm. There is, therefore, enormous reliance and relies enormously on irrigation for food production of its ballooning population as well as for industrial raw materials. The sustainability of this major sector of the country's economy is at risk because of inefficient irrigation practices besides escalating water scarcity. Realizing the situation, recently a number of interventions have been introduced for water conservation and productivity enhancement in Punjab's agriculture. Drip irrigation has emerged as one such method having substantial water savings and productivity gains in comparison to the crops cultivated under conventional irrigation. The water saving under drip irrigation was 50 percent and increase in yield was 34, 39 and 105 percent for potato, sugarcane and citrus, respectively with several allied remunerations including irrigation cost curtailment, enhanced quality of produce etc. The study also investigated potential areas for drip technology to efficiently utilize the available farm level irrigation supplies.*

Keywords. Irrigated Agriculture, Drip Irrigation, HEIS, Punjab, OFWM, PIPIP

1. INTRODUCTION

As in many parts of the world, irrigated agriculture is one of the major contributors to economic development in Pakistan. Irrigation consumes about 85 percent of available water in developing countries and 62 percent in developed countries (Mark, 2010). In arid climates like Pakistan, where an average annual rainfall is less than 240 millimeter, role of irrigation becomes very crucial in sustaining agriculture (John et al., 2006). Evidently, more than 80 percent of Pakistan's cultivated land is irrigated, whereas this ratio further jumps to 86 percent in case of the Punjab province. The contribution of irrigated lands to total national agricultural output is more than 90 percent (PDS, 2011 and Khan, 2006) revealing unquestionably the conspicuous prominence of irrigated agriculture in Pakistan. The sector has strong linkages with almost all major sectors of the economy as it absorbs 45 percent of total labor force and contributes substantially to exports by supplying raw materials to downstream industry. Despite its critical importance to national development, the sector could not perform sustainably because of structural issues, lack of mechanization and water shortages. Amid many problems, adequate water availability and its efficient use for crop production remained the main impediment to low productivity (PES, 2011). The level of agricultural production is directly related to the availability and effective use of water as a major input. Efficient use of all other production inputs depends on adequate irrigation for crop production (Bakhsh et al., 2008).

The balance between population and available water already makes Pakistan one of the most water stressed countries of the world. According to a study published by the World Bank (2006), "*Pakistan's Water Economy: Running Dry*", Pakistan is one of the most water-stressed countries in the world and its performance in terms of capacity, water use as well as quality has remained poor despite having enormous potential for water resource development and management. If the current trend continues, it will soon enter a condition of absolute water scarcity (Figure 1). Irrigated agriculture utilizes only 30 percent (42 million acre foot) of available water resources for crop production (Khan, 2006 & Mahmood, 2012).

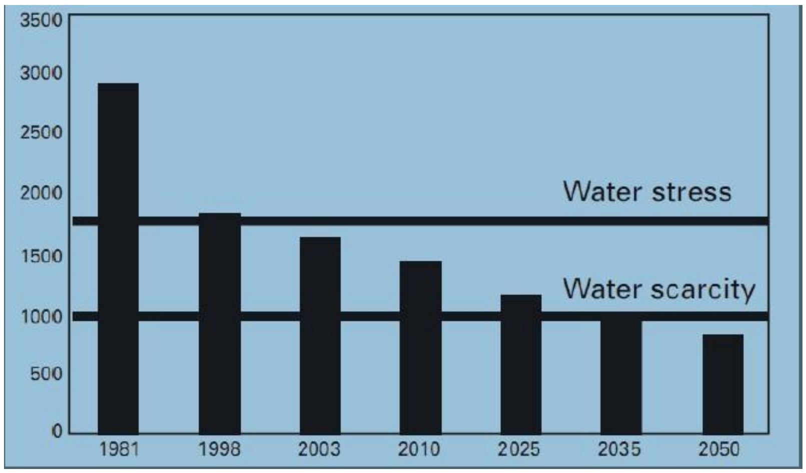

Figure 1. Water availability (m^3/capita)

Even though Pakistan has bestowed with largest contiguous Indus Basin Water System (IBWS), a huge volume of water is wasted in conveyance and application because of mismanagement. Furthermore, the IBWS was designed for low irrigation intensity (67 percent) and farmers are still practicing inefficient and unproductive traditional irrigation methods and practices (PDS, 2011). Crop water requirements are not met timely because of supply based irrigation water delivery, which negatively affects the overall productivity. The irrigation efficiencies at the farm level are dismally low that is a major constraint in attaining potential production from otherwise highly productive agricultural lands. Another peculiar threat is the unregulated groundwater abstractions at an alarming rate causing mining of subsurface reservoirs besides intrusion of saline water from brackish aquifers to freshwater areas. This is evident from the fact that the number of tubewells in only in Punjab has increased from less than 10,000 in 1960 to about 1,000,000 in 2011 (PDS, 2011).

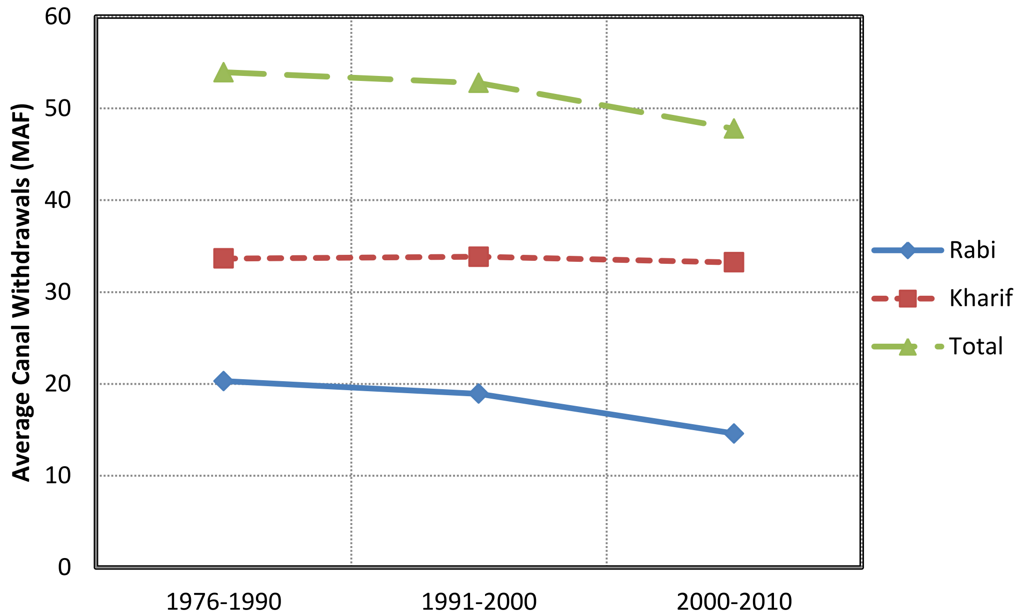

Figure-2: Average Canal Diversions (1976 to 2010)

The World Bank (2006) indicated that the water productivity for wheat in Punjab (Pakistan), California (USA), and Indian Punjab have shown productivity ratio of 5:8:10 per unit of water, respectively. Another study reported that water production in Pakistan is less than 0.1 kg/m^3 as compared to 0.39 kg/m^3 in India (PES, 2011). In view of escalating water shortages and rapidly increasing demands, the situation would simply be unsustainable for irrigated agriculture on which national economy is based. Resultantly, the efficient and judicious of scarce irrigation supplies through adopting water conservation and resource productive technologies for maximizing per unit production of water is inevitable.

There is now the emergence of a class of farmers who are growing high-value crops for both domestic and export markets, and are willing to invest in and adopt better and advanced irrigation practices, in which water plays a central role not just in evapotranspiration, but as a mechanism for delivering fertilizers and pesticides to crops.

Raising crop water productivity is the cornerstone of any demand management strategy to sustain crop production under escalating water shortages. In recent past, micro irrigation technologies called as high efficiency irrigation systems (HEISs) have been introduced in the country on a larger scale for enhancing water use efficiency and improving crop water productivity. Several studies have proved the technically feasibility, economic viability, and environmental compatibility of these micro irrigation systems in terms of water saving and yield increase. Keeping in view the potential of this technology, an attempt has been made in this paper to contemplate the issues and strategy relating to adoption of drip and sprinkler irrigation in Punjab.

2. The Issues

Irrigated agriculture is the central framework around which the entire economic and social fabric of Pakistan's development is woven. While the transition to an urban and industrial economy can and must continue, agriculture will remain central for the well-being of large number of people. Better water management is a key constraint to improving agricultural productivity and generating jobs. There is no denying that this sector requires more and more attention to bring it at par with developed nations if the country is to avert ever nearing looming food disaster. To formulate a viable strategy it is, however, necessary to ascertain some of the major issues related to irrigated agricultural production. The complexity and intertwining of myriad problems in boosting production per unit of water is beyond the scope of this paper and attention is focused on major issues.

2.1 Land Resources

Demographically, Punjab is the largest province of Pakistan with a total geographical area of 20.64 million hectares (Mha), out of which 0.50 Mha (2.42%) are under forests, 3.04 Mha (14.7%) are uncultivable, 3.88 MA (7.6%) are culturable waste, 7.28 MA (14.9%) are non-reported, 1.57 Mha (7.5%) are currently fallow and 11.03 Mha (53.5%) are net sown. Nearly 76 percent of irrigated area lies in Punjab. Its share in total agricultural production of the country is more than 80 percent in case of cotton, almost 70 percent for wheat, nearly 60 percent for sugarcane, and 50 percent in rice. Over all contribution of the province towards agriculture sector is estimated to be more than 80 percent. Geographically, the province is situated at the center of the World's largest Indus Basin link canal irrigation system and has the greatest irrigated area and largest amount of irrigation assets in Pakistan. Despite its everlasting significance, the province is facing acute water shortages creating threats for food security to its people.

2.2 Surface Water Resources

The single most irrefutable factor in Pakistan's water resources is that there is near future no more additional surface water that can be injected into the system. In the present situation there is no feasible intervention which would enable the country to mobilize appreciably more water than it now uses. On the contrary, the international scenario indicates decreased flows in some rivers. Furthermore, if environmental concerns in the delta areas are to be addressed, there is an argument for reducing the overall use for irrigation needs in upper agricultural areas.

The water economy of Pakistan depends fundamentally on a huge and complex hydraulic infrastructure system known as the Indus Basin Water System. Significant portions of this system are now reaching the end of their design lives, and have to be rebuilt or repaired. This dependence on a single river system also means that there is little room for maneuvering that most countries enjoy by virtue of having a multiplicity of river basins and diversity of water resources. If the system fails there is no latitude for error.

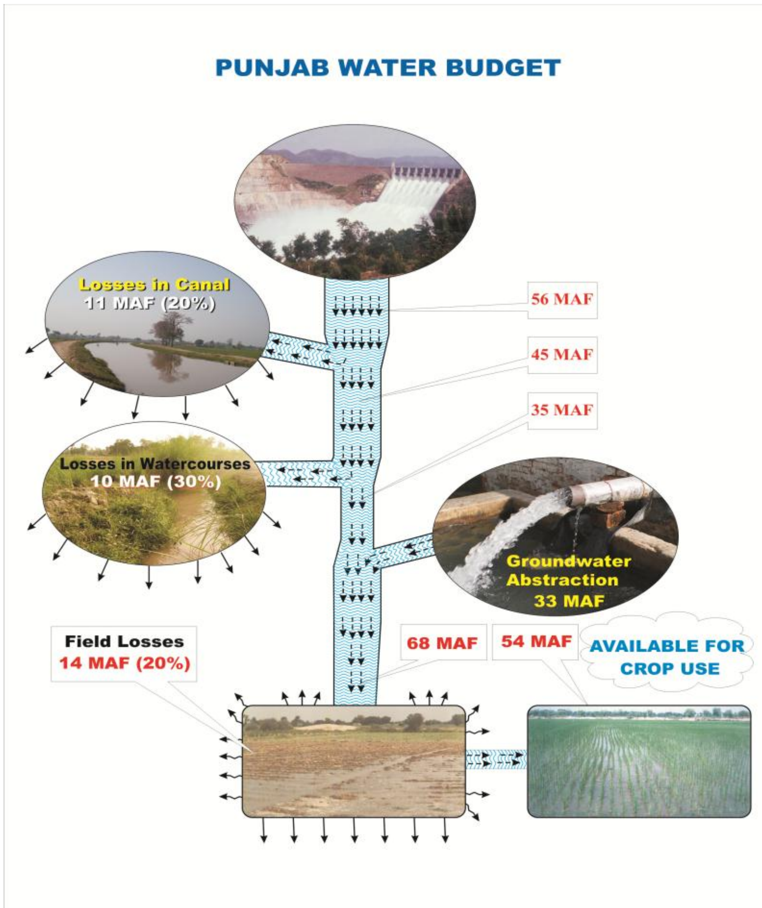

Figure-3: Punjab Water Budget

The total surface water allocation for the Punjab as per Water Accord 1991 is 55.54 MAF. An analysis of canal water withdrawals during Rabi and Kharif from 1976 to 2011 has shown a declining trend as shown in (Figure-3). The canal water supplies have declined to 47.80 MAF in the last decade. This is due to reduced reservoirs storage capacity because of sedimentation. Rabi has shown a major deficit of 5 MAF compared to water withdrawal in 1976. Moreover, there are huge water losses in the distribution network comprising of main/branch canals, distributaries, minors, and tertiary conveyance systems comprising of about 58,000 watercourses. According to Khan 2006, only 45 percent of diverted water into the canals is used for intended purposes and remainder lost in conveyance. The only possibility of augmenting water supplies is through heavy investment in storage dams on the Indus River which is controversial. With continuing sedimentation of major reservoirs, the increase in canal diversions with new dams is uncertain.

2.3 Groundwater Resources

Over the past 40 years, the exploitation of groundwater, mostly by private farmers, has brought enormous economic and environmental benefits. Groundwater now accounts for more than half of all irrigation requirements. Punjab withdraws almost 50 MAF of water from groundwater, which has reached its limit and further withdrawals are not possible without serious mining and extraordinary cost of pumping. Now, although, there is clear evidence that groundwater is being over-exploited, yet tens of thousands of additional wells are being put into service every year. In the sweet water areas of the Indus Basin, depletion is now a fact in all canal commands. Furthermore, there are serious and growing problems with groundwater quality, a reality that is likely to get worse because there are 20 million tons of salt accumulating in the system every year.

The current approach to groundwater pumping is of laissez-faire, there being no regulation or policies to govern this sector. There is an urgent need to develop policies and approaches for bringing water withdrawals into balance with recharge. Since much groundwater recharge in the Indus Basin is from canals, an integrated approach to surface and groundwater is required.

2.4 Institutions

The main canal network is operated and managed by the Provincial Irrigation Department. Beyond the farm outlet, however, the system is run by the water users. The On Farm Water Management wing of the Provincial Agriculture Department is the primary agency for promoting resource conservation technologies, which are contributing significantly in enhancing water availability at the farm level and minimizing water losses to a great extent since 1976-77. There has been no incremental water resources development taken place during this period in the province. The only source of increased water availability at the farm level has been through adoption of conservation measures e.g. canal rehabilitation and lining, improvement of watercourses, LASER land leveling, bed and furrow irrigation etc. Farmer institutions are organized as Water Users Associations (WUAs) under an Act. These WUAs have an active participatory role in most of the water conservation activities implemented by OFWM.

Conceptually the task to move water in a predictable, timely manner to those who have a right to it and to ensure its efficient and judicious use seems relatively simple. Yet this has not been the case. It has been a slow and painstaking process leading from basic conservation practices like watercourse remodeling to more and more advanced techniques like high efficiency irrigation systems over a span of more than 30 years.

2.5 Productivity

As indicated earlier, there is abundant evidence that irrigated agriculture in Punjab is not efficient. It is becoming increasingly apparent that water not land is the main constraint, and the focus of attention will have to shift from productivity per unit of land to productivity per unit of water. The major challenge is to get more from less – more crops, more income, more jobs per unit of water. Recently, there is growing attention to the different water requirements of different crops. An acre of sugar-cane, for example, consumes as much as eight times the water needed by sugar bet. Increased attention is accordingly now being given to producing crops that can yield more with less water, withstand water-scarce and drought conditions, and thrive on low-quality (saline/alkaline) water and to the effect of different agronomic practices on water productivity.

Improving the productivity of water used in agriculture is a central challenge facing a water-scarce Punjab. It has been determined that the water required to grow enough food for one person – between 3,000 and 5,000 cubic meters a year – is about 100 times the amount required for household purposes (100 lpd or about 35 cubic meters a year). Accordingly, urban demands are important locally but not at a national scale.

3. Past Efforts

On Farm Water Management (OFWM) program has successfully promoted resource conservation technologies in Punjab which are contributing significantly in enhancing water availability at the farm level and minimizing water losses to a great extent since 1976-77. Since there has been no incremental water resources development taken place during this period in the province, the only source of additional water at the farm level has been through adoption of conservation measures e.g. canal rehabilitation and lining, improvement of watercourses, LASER land leveling, bed and furrow irrigation etc. Over the years there has been a gradual transition from elementary conservation practices like remodeling of earthen watercourses to the relatively more complex interventions like high efficiency irrigation systems.

Most of early OFWM projects were funded through assistance of donor agencies till last decade when the Government implemented some major initiatives out of its own resources. A mega initiative “National Program for Improvement of Watercourses (NPIW)” was launched in 2004 to improve the tertiary level irrigation conveyance system through a community driven implementation approach. Improvement of about 19,000 canal commanded watercourses and development/ rehabilitation of 3,734 irrigation schemes outside the canal commands have been completed during 2004-2011.

Similarly, a major project for provision of subsidized LASER land leveling equipment to farmers and service providers was launched in 2005, wherein 2,500 systems were provided. The scheme proved to be highly beneficial due to its immediate impact in minimizing cost of operation, better degree of accuracy in lesser time, saving of irrigation water, uniform seed germination, increased fertilizer use efficiency, and resultantly enhanced crop yields.

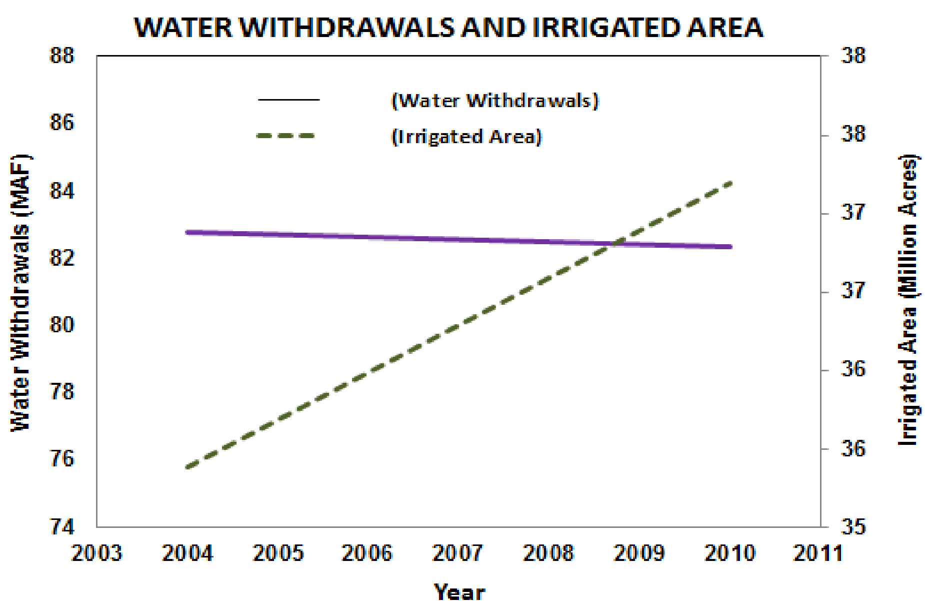

Figure-4: Water Withdrawals versus Irrigated Area

In the introduction of HEIS, a number of attempts were made in the past by various organizations including OFWM on a limited scale. Such efforts did not gain much acceptance among the farming community despite the obvious water saving benefits. Analysis of the reasons for failure of these projects indicated following major issues;

a. Lack of organization/institutional support for technical assistance and capacity building.
b. Insufficient technical expertise and knowledge base in designing, installation and operation
c. Inefficient technological package for follow-up and crop establishment i.e. irrigation schedule and fertigation schedule, plant protection and other agronomic practices.
d. Inadequate participation and knowhow of all stakeholders at planning, designing, installation and operation
e. Ineffective follow-up for assisting the farmers to successfully adopt the new technology
f. High initial cost of the system that requires fixed investment

The project titled "Water Conservation and Productivity Enhancement through High Efficiency (Pressurized) Irrigation Systems", called HEIS project, was launched to install drip and sprinkler irrigation on about 140,000 acres during four years (2008-09 to 2011-12) at a total subsidized cost of Rs. 6,917 million in the entire province. The project was implemented by OFWM through pre-qualified supply and services companies (SSCs), which installed the systems on turnkey basis in farmer's field. Under 18th constitutional amendment, this project was, however, abandoned because of some administrative and financial problems regardless of its encouraging impacts. Under the scheme HEIS, systems were installed on 9,500 acres spread over the entire Punjab. The system-wise breakup of the installed systems is given in Table-1 below.

As evident from Table-1, drip technology has major share covering over 68 percent including orchards (32 percent) and row crops (26 percent). The sprinklers are installed on 32 percent of total area for cereal crops to supplement rainfall in rain-fed tracts and provide light irrigations in canal commands. This indicates a clear need and preference for drip irrigation over sprinkler irrigation systems.

Table 1: Distribution of Installed Drip Irrigation Systems in Punjab

Particulars	**Micro Irrigation**	
	Acres	**% of total**
Total Installed systems	11,500	100
Drip	*7,850*	*68*
Sprinkler	*3,650*	*32*
Drip Systems		
Orchards	4,870	62
Citrus	*2,625*	*33*
Mango	*1,200*	*15*
Others	*1,045*	*13*

Row Crops	2,980	38
Cotton	*2,135*	*27*
Sugarcane	*240*	*3*
Vegetables	*605*	*8*

The Government of Punjab also implemented an innovative undertaking for promotion of cotton cultivation under desert environment with drip irrigation on 2,000 acres at a total cost of Rs. 267 million during two years (2009-10 to 2010-11). The "Pilot Project for Promotion of Cotton Cultivation in Thal Region with Drip Irrigation" was designed to harness maximum potential of land, water, and other inputs for increasing agricultural productivity demonstrating cotton cultivation in water scare desert environment though effective utilization of irrigation water under drip irrigation. The farmers were provided 90 percent of the total system cost in addition to construction cost for water storage pond required for drip irrigation system. The project achieved considerable success wherein, it was reported that cotton yielded upto 1.86 tons per acre with an average of 1.12 tons per acre vis-à-vis 0.60 tons per acre average in the area. Drip irrigation also made it possible to grow cash crops first time on sand dunes without land leveling in the project area including oil seeds, onion, vegetables in tunnels, maize, water melon etc.

4. Strategy

The experiences and lessons learnt during implementation of above two projects led to the development of strategy and design of a major initiative titled "Punjab Irrigated-Agriculture Productivity Improvement Project (PIPIP)", which has been set forth to maximize output of available water by adopting a comprehensive OFWM technological package for minimizing losses at various levels of tertiary conveyance network and improving its application efficiency at the farm level. The project has been formulated based on following strategic considerations.

4.1 Feasibility of Drip Irrigation in Punjab

Foremost, it is necessary to determine the efficacy and quantum of benefits to be accrued with investments in drip irrigation systems under conditions in Punjab. Experiments at Mona Reclamation Experimental Project (MREP), International Waterlogging and Salinity Research Institute (IWASRI), reported about 85 percent water saving as compared to conventional irrigation for citrus crop. Trials at the Nuclear Institute for Agriculture and Biology (NIAB), Faisalabad to compare effects of 15% (D15) and 30% (D30) deficit irrigations on water use efficiency of cotton in comparison to no deficit (D0) irrigation using drip irrigation system. The D0 treatment produced 8% and 33% more cotton yield than of was those of D15 and D30, respectively. Likewise, the water use efficiency of D15 was 5% more than D0 and 15% more than D30. The study concluded that drip irrigation has the potential of increasing water productivity even under deficit irrigation environment. In another study on adoptability of trickle irrigation system for small farmers in Punjab and found 50%, 47% and 43% water saving for cotton, sugarcane and chilies, respectively.

Some impact assessment studies for performance evaluation of drip/sprinkler irrigation on different crops were undertaken by technical committees of Punjab Agriculture Department. The performance of the drip irrigation system showed 57 percent water saving in case of sugarcane while 50 percent for both citrus and potato crops against conventional irrigation methods. The increase in yield in drip irrigated areas was 34, 39 and 105 percent for potato, sugarcane and citrus, respectively as show in Table-2.

Table-2: Increase in Yield in Drip Irrigated Areas

Sr. #	Particular	Sugarcane (R.Y.Khan)	Citrus (Layyah)	Potato (Chiniot)
1	Water saving	57	50	50
2	Enhancement in yield	39	105	34
3	Saving in fertilizer application	28	-	40
4	Reduction in labor	60	-	-
5	Curtailing irrigation cost	-	72	-
6	Increase in juicy contents	-	30	-
7	Sugar recovery	11.2	-	-

Sugarcane is one of the major row crops suitable for drip irrigation. Input management was the key difference in drip irrigation over the conventional surface flooding method by providing efficient, balanced, and timely inputs. Accordingly, the fields under drip irrigation exhibited uniform sugarcane stand with 16 percent longer nodes, 25 percent more tillers, and 24 percent lengthy millible cane. All these factors contributed towards significantly increased weight per cane in fields under drip irrigation. It was reported that entire farm area could be cropped after adoption of drip irrigation whereas previously almost half the farm land used to remain uncultivated due to water shortage.

Potato is another row crop that was adopted successfully on drip irrigation. In arid regions, potato is sensitive to water stress and irrigation has become very essential in comparison with the other crops as it needs frequent irrigation for suitable growth and optimum yield. In district Chiniot, an early potato variety Kuroda (Red Skinned) was planted on 17 acres with drip irrigation, 2 acres under sprinkler irrigation and 19.5 acres with flood irrigation. Drip irrigated field gave 34 percent more yield as compared to flood irrigation whereas the increase in yield was 9 percent in case of sprinkler irrigation. In addition to significant increase in yield under drip irrigation, 50 percent saving of water and 30 percent reduction in weeds attack were also observed under drip irrigation compared to flood irrigation.

The drip irrigation of citrus orchards started exhibiting its effects after a very short period in terms of visual plant growth. Moreover, drip irrigation offers/facilitates dense orchard planting, which is the simplest and most effective means of increasing yield. Planting of about 10,329 extra plants (47 plants per acre) could be possible only with drip irrigation by reducing interplant distance due to judicial use of water. There was about 58 percent increase in plant population per acre which will manifold the benefits of drip irrigation on reaching fruiting stage. The mortality rate of 10-15 percent under flood irrigation became negligible with drip irrigation of young plants because of timely and balanced application of inputs. It was reported that drip technology has saved 85 percent water for citrus crop as compared to farmer’s conventional method. Another study showed that water productivity with drip irrigation for citrus was as high as 450 percent as compared with traditional farming method.

Table-3: Fruit Quality Characteristics of Citrus (Kinnow)

Sr. No.	Fruit Quality Characters	PHDEB* Standards	Drip Adopted Area
1.	Average Fruit Weight (g)	160	166.23
2.	Average Size (mm)	45	66.88
3.	Peel Thickness (mm)	3.5	4.2
4.	Peel (%)	35	35.3
5.	Juice (%)	33	37
6.	T.S.S. (%)	10	12.9
7.	Acidity (%)	1.0 (max)	0.81
8.	Taste	Good	Good

* Pakistan Horticultural Development & Export Board

Furthermore, the citrus produced under drip irrigation have better physiochemical characteristics. Size is the most common and impressing factor used for assessing the quality of citrus. The citrus produced under drip irrigation was found intact, sound, clean, and more importantly of uniform size. The average weight, size, peel thickness, peel content, TSS and juice percentage are contributing factors towards improved fruit quality under drip irrigation, which ultimately led to higher sale price of the orchard. The quality characters of citrus grown with drip irrigation fulfilled all minimum quality requirements set by Pakistan Horticultural Development and Export Board.

Figure-5: Pictorial view of installed HEIS in Punjab

4.2 Implementation Strategy

The Punjab Irrigated-Agriculture Productivity Improvement Project (PIPIP) envisages installation of drip and sprinkler irrigation systems on 120,000 acres. The overall project development objective (PDO) of PIPIP is to improve water productivity i.e. producing more crop per drop which will be achieved through increasing delivery efficiency, adopting improved irrigation practices, promoting crop diversification, and effective application of non-water inputs.

As HEIS is still the new technology in Pakistan, expertise is lacking with all stakeholders including supply & service companies (SSCs), OFWM staff, consultants and farmers. On initiation of HEIS scheme, over 50 SSCs came forward for provision of services related to drip and sprinkler irrigation but the on and off modes of the project have discouraged the private sector to fully develop its capacity and build confidence about continuity of government support. Moreover, there are several issues to be resolved through adaptive research for technology indigenization. These issues have considerably been incorporated in the modified approach under PIPIP as the technology is not getting its due course of momentum and popularity.

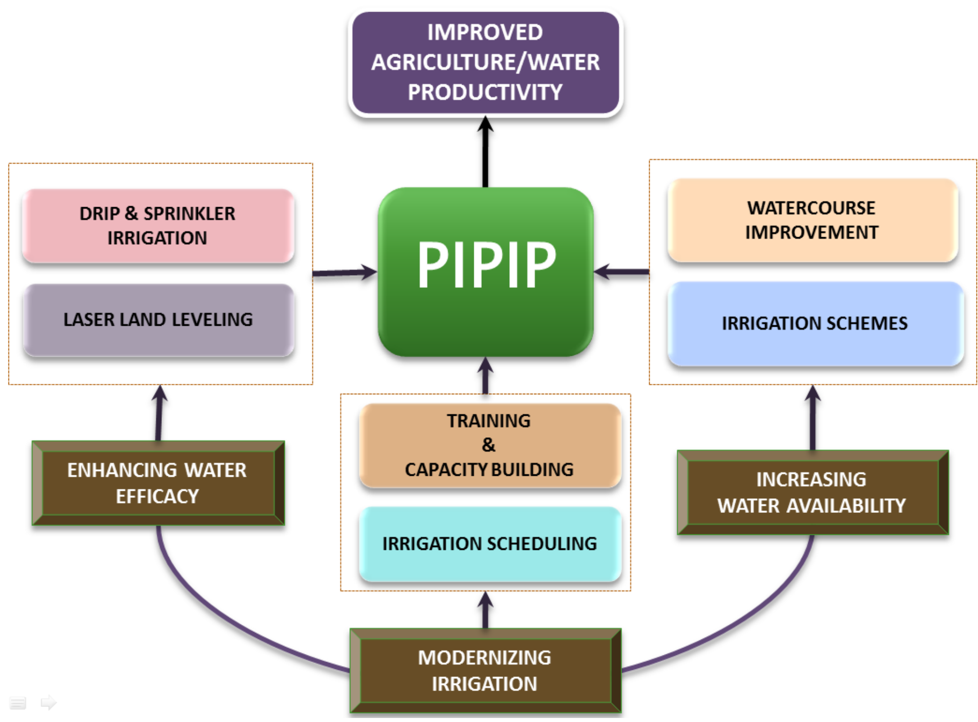

Figure-6: PIPIP Conceptual Framework

The crop production under high efficiency irrigation requires fundamental change in the irrigated agriculture. Accordingly, under PIPIP, the successful promotion and adoption of these technologies has been well addressed through awareness, demonstration, service provision, backup support, training and capacity building as well as research and indigenization. As the role of SSCs, being the major stakeholder in project implementation is very crucial. So, strenuous efforts have been made to encourage private sector for involvement in provision of various services related to high efficiency irrigation. The prime objective of PIPIP in this regard is to:

- Built confidence of service providers for assured sizeable market/clientage
- Create enabling environment for existing pipe and plastic industry to start local manufacturing of drip/sprinkler components for technology indigenization
- Encourage the firms for establishment of service provision network / backup support centers at regional/district level

Apart from the government efforts, private sector suppliers and manufacturers, extension workers, and research institutes need to play their role in promoting these resources conservation technologies. The implementation role of the various stakeholders is indicated at Figure-4.

The major components of the implementation strategy accordingly include;

a) Launching of a province wide awareness campaign in print and electronic media as well as establishment of demonstration sites and information centers/kiosks.
b) Input of international experts both institutional and individual for professional guidance and assistance in technical aspects of engineering, agronomy, horticulture, soil sciences etc.
c) Capacity building of all stakeholders including farmers, project staff, SSC personnel, supervisory consultants etc.
d) Conduct on-going research and development for further fine tune various parameters of project implementation.
e) Establishment of materials and equipment testing facility.
f) Surveys and designs by registered independent private sector service and supply companies.
g) Cost sharing of the system with farmers contributing 40 percent of the cost of system.
h) Decision making at Provincial, Regional and District level
i) Third party inspection and validation of designs and works
j) Continuous monitoring and evaluation
k) Future planning

5. Way Forward

Water scarcity is the biggest challenge confronted by irrigated agriculture in the Punjab. The level of agricultural production heavily depends on water availability and its efficient use as a major input. Under prevailing water scarceness, the sustainability of irrigated agriculture is at risk and adoption of high efficient irrigation modern irrigation techniques and methods, offering water conservation and yield enhancement, is inescapable. Punjab has about 1.57 M i.e. eight percent of total geographical area, of cultivable wastelands. To cope with the dwindling land and water resources, it is viable to exploit all the available resources sustainable for producing enough foods to meet the future demands. A logical way forward is to develop the cultivable wastelands for crop production. These include two major areas of the Pothowar Plateau and Thal Region in the province.

5.1 Pothwar Plateau

The Pothwar Plateau, covering an area of 2.2 Mha, is an arid landscape with denuded and broken terrain characterized by undulations and irregularities. The climate is favorable for crop production on fertile soils having no major problem of salinity and water logging. The occurrence of rainfall is, however, highly erratic both in space and time that demands water harvesting, storage, and supplemental irrigation for successful crop production in the region. Reportedly, about 3.40 MAF water is lost from the area due to surface runoff annually. The total area under cultivation in this area is about 1.0 Mha and agriculture is at sustenance level mainly because of assured irrigation supplies shortages.

The Small Dams Organization (SDO) of Provincial Irrigation Department, so far, has constructed 48 dams in Pothwar region, which are designed to irrigate over 50,000 acres. The command area of these dams has, however, not been developed substantially. The cropping intensity is also very low (about 50 percent) against planned average of provincial Irrigation Department. Nevertheless, there is high potential for the development of irrigated agriculture in the region by managing supplemental irrigation through storage of runoff water and irrigating crops with high efficiency irrigation systems i.e. drip and sprinkle.

5.2 Thal Region

Thal is a vast desert in Punjab with undulating topography consisting of large sand dunes, which often keep on shifting from one place to another due to random wind storms action. It encompasses entire districts of Bhakkar and Layyah as well as parts of Khushab, Mianwali, Jhang, and part of Muzaffargarh district spreading over an area of about 7 MA. The land in the Thal is generally undulating and soils are sandy in nature having extremely low water holding capacity. The gravity irrigation through conventional practices on such soils is grossly inefficient resulting in precious water wastage through seepages. Thal has following comparative advantages for application of drip irrigation.

- The groundwater is mostly suitable for irrigation and available at appropriate depth, which is recharged by perennial rivers (Indus and Jhelum).
- The upper layer of the sandy soils in the area is very fertile having no waterlogging and salinity problems.
- Drip irrigation does not require leveling of undulating sand dunes that entails huge capital investment, time, and heavy machinery.
- Desert environment is less susceptible to insect/pest and diseases due to dry conditions.
- Climate is very conducive for cultivation of high value sensitive crops e.g. cotton, vegetables.

The command areas of newly developed canal systems like Greater Thal Canal (GTC) may be developed using modern irrigation. There are some areas where the canal water supplies are limited only for 80 percent of cropping intensity because of which vast land remains uncultivated every year which could be brought under cultivation through drip irrigation systems under limited water supplies.

6. Conclusion

The preceding discussion suggests that the potential of drip and sprinkler irrigation is huge in different regions across the Punjab. The adoption of these technologies is, however, not appreciable as fraction of a percent of total cultivated land is under micro irrigation. Given the benefits of high efficiency irrigation in terms of water saving and productivity increase, its gross benefits would be enormous, if the available potential is utilized.

The study clearly demonstrates that drip irrigation have many advantages over conventional flooding that is primarily followed in Punjab. Drip irrigation, being the most efficient irrigation system, reduces cost of production as well as increases crop productivity. Drip irrigation facilitates raising of tropical crops like sugarcane in arid climates and offers dense planting of orchard as well as cotton cultivation under drip irrigation in Thal has proved highly efficacious. Acquired benefits of this resource conserving technology suggest its adoption on larger scale, especially in the potential areas in first stage. Since the adoption of drip and sprinkler systems is in the take-off phase in Pakistan, an active role of the major stakeholders is pivotal in promoting these technologies as well as developing confidence among the farming community about the utility of this new technology.

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Evaluation of a Center Pivot Variable Rate Irrigation System

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Abstrat: Uniformity of water distribution of a variable rate center pivot irrigation system was evaluated. This 4-span center-pivot system was configured with 10 water application zones along its 766 ft-long lateral. Two experiments were conducted for the uniformity tests. In one test, a constant water application rate (100%) was applied, and in the other, variable application rates (0%, 30%, 50%, 70%, and 100%) were assigned to each zone. To catch water applied, multiple water collectors were placed in two straight lines perpendicular to the pivot travel direction. Three control collectors with known amounts of water were placed at the test site to account for water evaporation losses during the tests. Water caught in the collectors was measured, and the center pivot coefficient of uniformity (CU_H) was calculated. Results showed a CU_H of 86.5% for the constant application rate test. The effect of application rate on CU_H was significant, with higher application rates providing higher CU_H values.

Keywords: Irrigation, variable rate application, center-pivot irrigation system, uniformity, precision agriculture

INTRODUCTION

Uncertainty in the amount and timing of precipitation is one of the most serious risks to crop producers in the Mid-South. In recent years, producers in this region have become increasingly reliant on supplemental irrigation to ensure adequate yields and reduce risks of production. Increasing groundwater withdrawal is resulting in a decline in aquifer levels across the region. For sustainable water use in agriculture, increasing water-use efficiency in agricultural production has become a serious issue. Compared to furrow-irrigation methods, sprinkler systems can significantly improve irrigation efficiency, and their use is increasing in the Mid-South.

In the most of agricultural fields, soil characteristics and plant growth status considerably vary within a field. Plants in one location may need more inputs, such as water or fertilizer, than the plants in another location in the field. Treating plants differently based on their needs is required for optimizing crop yield and quality. Precision agriculture technologies make it possible for farmers to adjust production inputs site-specifically to address the spatial variability in the field. Sprinkler irrigation systems equipped with variable rate irrigation (VRI) controllers are now commercially available. Currently two primary control methods are used to realize VRI; speed control and duty-cycle control (LaRue and Evans, 2012). The speed control method varies travel speed of the center pivot to accomplish the desired application depth, while the duty-cycle control changes the duty cycle of individual sprinklers or a group of sprinklers.

Currently there is no standard method for evaluating a VRI system capable of making site-specific water application for precision agriculture practices. Limited work has been reported on the evaluation of VRI performance yet. The accuracy and uniformity of the system are essential for the success of precision irrigation management.

The objective of this study was to evaluate the accuracy and uniformity of a center-pivot irrigation system equipped with a VRI zone control package.

MATERIALS AND METHODS

System description

The center pivot VRI system used in this research was a Valley Standard Pivot 8000 coupled with the Valley VRI zone control package (Valmont Irrigation, Valley, NE). The system was installed at a research farm of the USDA-ARS Crop Production Systems Research Unit at Stoneville, Mississippi in November 2011 (Figure 1). The system was configured with a total length of 766 ft, with 4 drive units and a flow rate of 350 gpm. Fixed-pad sprinklers (Senninger LDN, Clermont, FL) were employed with UP3 flat medium groove pads and 15 psi pressure regulators. The distance from the sprinkler to ground surface was 72 in. Sprinkler spacing was 108 in, and 86 sprinklers along the length of the pivot lateral were divided into 10 control zones based on covered surface area.

The Valley zone control package included 5 VRI zone control units, a GPS receiver, and software. The control units and the GPS receiver were mounted on the top of pivot towers. Each VRI zone control unit controls the duty cycle of the sprinklers in two independent zones by turning on/off electric solenoid valves to achieve desired application depths in individual zones. The GPS receiver determines the pivot position for identification of the control zone in real time. VRI prescriptions can be created using the software provided in the package and wirelessly loaded up to the system.

Experiment setup

The system was tested under both constant application rate and variable application rate conditions. New plastic cups with a 3.5-in diameter opening and 5-in depth were used as collectors to measure the depth of water applied. Each collector was taped onto a wood stake which was inserted into the soil (Figures 2 and 3). The distance between the ground surface and the collector opening was approximately 8 in. The collectors were uniformly spaced along two straight lines perpendicular to the direction of travel of the pivot. The angle between the two lines of collectors was 12 degrees. In accordance with ASABE Standard S436.1 (ASABE Standards, 2007), no collectors were placed within the inner 20% of the effective radius of the pivot, 145 ft in this case. In the constant application rate test, 78 collectors were placed with a spacing of 8 ft in each line. In the variable rate test, 3 more collectors were added between each control zone, for a total of 105 collectors in each line. Details of the control zones and desired application rates are presented in Table 1.

To make adjustments to the collected data to account for evaporation from collectors, three collectors containing known amounts of water similar to the anticipated catch were placed at the test site. Water remaining in the control collectors was measured at the end of the test and combined with the recorded time to determine evaporation occurring during the tests.

Test procedures

The constant rate test was conducted on March 15, 2012 and the variable rate test on March 26, 2012. The pivot started at approximately 12 degrees before reaching the 1st test line to allow the water pressure of the system to stabilize at the desired testing conditions.

The application depth was set at 1 in for constant rate test. For the variable rate test, the 10 control zones were randomly assigned to 5 different application rates; 0, 30%, 50%, 70%, and 100%. The 100% rate corresponded to an application depth of 1 in.

The volume of water collected in each collector was measured using a graduated cylinder immediately after the pivot passed the test line and no more water from the sprinklers reached the collector (Figure 4). The volume of water was then converted to the depth applied based on the dimensions of the collector cups.

During the tests, the air temperature was around 78 F. The wind speed was approximately 7-8 mph S.

Data analysis

The center pivot coefficient of uniformity was calculated using the formula of Heermann and Hein (ASABE Standards, 2007)

$$CU_H = 100\left[1 - \frac{\sum_{i=1}^{n} S_i \left|V_i - \overline{V}_p\right|}{\sum_{i=1}^{n} V_i S_i}\right]$$

where

CU_H is the Heermann and Hein uniformity coefficient;

n is the number of collectors;

i indicates the i^{th} collector;

V_i is the volume of water collected in the i^{th} collector;

S_i is the distance of the i^{th} collector from the pivot point;

$\overline{V_p}$ is the weighted average of the volume of water caught.

$\overline{V_p}$ was determined as

$$\overline{V}_p = \frac{\sum_{i=1}^{n} V_i S_i}{\sum_{i-1}^{n} S_i}$$

The mean of the applied depth and its difference from the desired depth was then computed.

For the variable application test, applied water depths in various control zones were calculated following the same procedure. Applied amounts in the area between control zones were also determined for comparison with the applied depths in the adjacent zones. An ANOVA was performed with SAS software (SAS Institute Inc., Cary, NC) to compare the effect of the application rate on the uniformity of the pivot.

RESULTS AND DISCUSSION

Constant rate test

The water depths measured by the collectors are plotted in Figure 5. The average uniformity coefficient of the pivot was 86.47% with a value of 86.45% in the 1st test line and 86.49% in the 2nd test line. There were several large fluctuations in the depth values, caused mainly by the locations where the collectors were placed. Some collectors were located very close to a pivot tire or at the end of a test line. The mean of the depth applied was 1.05 in, with a standard deviation of 0.18 in. Compared with the desired depth of 1 in, the difference between the amount applied and the desired depth was 5%.

Variable rate test

The uniformity test results for the variable rate test are shown in Tables 2 and 3. The ANOVA test revealed that there was a significant effect of the application rate assigned to the control zone on the uniformity coefficient [$F(4, 9)=115.97$, $p=0.0001$]. Very low uniformity coefficients were observed in zones 2 and 10, which had zero application rates. The uniformities in zones 3 and 7, which had an application rate of 30%, were also noticeably lower than the other zones. This indicated that low application rates could possibly introduce poor uniformity. This result was consistent with that reported by other researchers (Perry et al., 2003)

Applied depths and desired depths are plotted in Figure 6. Application amounts followed the desired values as a general trend. The means of applied depths for each zone are reported in Table 2, and again show that the lower the desired depth was, the greater the difference between the desired depth and the applied occurred. Figure 7 shows a comparison of measured depth in the zone and the depth in the adjacent areas between two zones. A gradual depth change between two zones with different application rates was consistently observed.

SUMMARY

Application of VRI technologies has great potential for farmers to optimize crop yield and minimize environmental impact. A center pivot VRI system was evaluated with both constant application rate and variable application rate. Under a constant application rate, a uniformity coefficient of 86.5% was observed, and the difference between the desired application amount and actual amount applied was 5%. A variable rate application test was conducted with five different application rates between 0 and 100%. The system performed well in zone control, and in general, the applied water depths followed the desired rate pattern. However, the effect of application rate on uniformity was significant. The uniformity under higher application rates was greater than that for application rates 30% or less. The variation in application rates between adjacent control zones was a gradual process instead of an ideally rapid change. This study was preliminary and more comprehensive evaluations on the VRI system performance are needed.

Disclaimer

The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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Table 1. Configuration of control zones and application rate assignments

Span No.	Zone No.	Rate (%)	No. of Collectors	Drops Per Zone
1&2	1	70	11	27
2	2	0	12	11
2&3	3	30	11	9
3	4	50	7	7
3&4	5	70	7	6
4	6	100	6	6
4	7	30	6	5
4	8	50	5	5
4	9	100	6	5
4&Overhang	10	0	7	4

Table 2. The uniformity coefficients in various control zones of the center pivot system.

Zone No.	Desired Depth (in)	Measured Depth (in)	CU_H in line 1 (%)	CU_H in line 2 (%)	CU_H average (%)
1	0.70	0.83	93.82	79.78	86.80
2	0.00	0.08	-18.36	-30.95	-24.65
3	0.30	0.31	78.58	86.09	82.33
4	0.50	0.53	86.18	84.49	85.34
5	0.70	0.72	85.51	92.19	88.85
6	1.00	0.99	91.01	85.20	88.10
7	0.30	0.52	75.54	70.29	72.92
8	0.50	0.61	91.68	69.93	80.80
9	1.00	0.96	94.00	84.48	89.24
10	0.00	0.13	-43.94	-44.03	-43.99

Table 3. The uniformity coefficients under various application rates. (*CU_H averages with the same character are not significantly different at 0.05 level.)

Rate (%)	CU_H in line 1 (%)		CU_H in line 2 (%)		CU_H average (%)*
	rep 1	rep 2	rep 1	rep 2	
0	-43.94	-18.36	-44.03	-30.95	-34.32[a]
30	75.54	78.58	70.29	86.09	77.63[b]
50	91.68	86.18	69.93	84.49	83.07[b]
70	85.51	93.82	92.19	79.78	87.82[b]
100	94.00	91.01	84.48	85.20	88.67[b]

Figure 1. Four-span Valley 8000 center-pivot variable-rate irrigation system.

Figure 2. Water collectors lined up to catch water applied.

Figure 3. Plastic cup to be used as the water collector.

Figure 4. Water was collected and measured using a graduated cylinder.

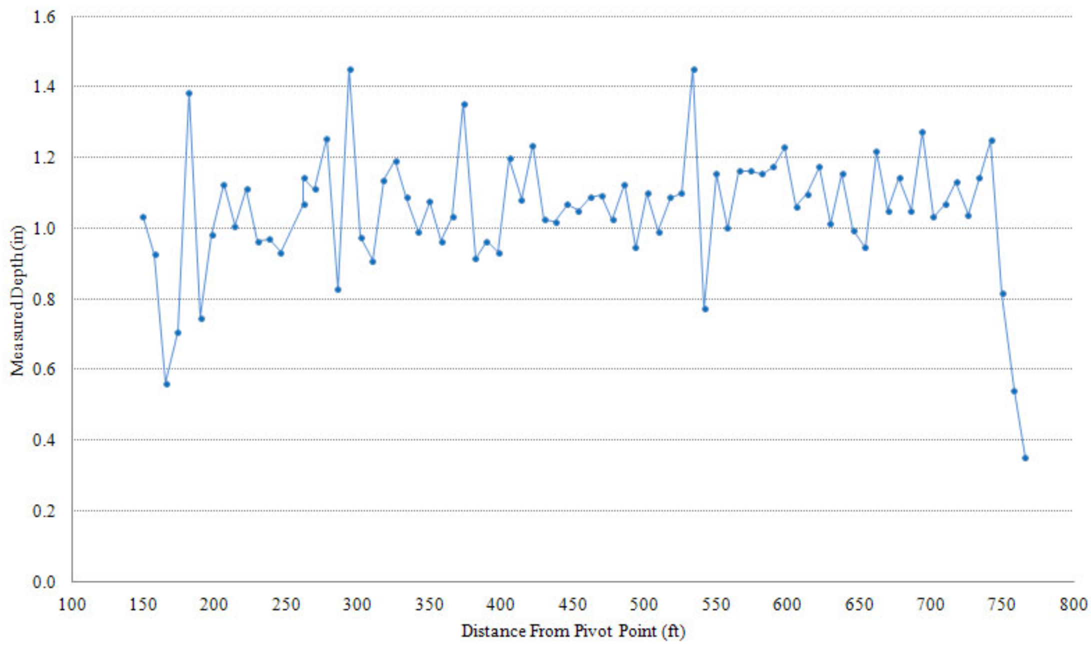

Figure 5. Water depth caught by the collectors in the constant rate test. The desired depth was 2.54 cm.

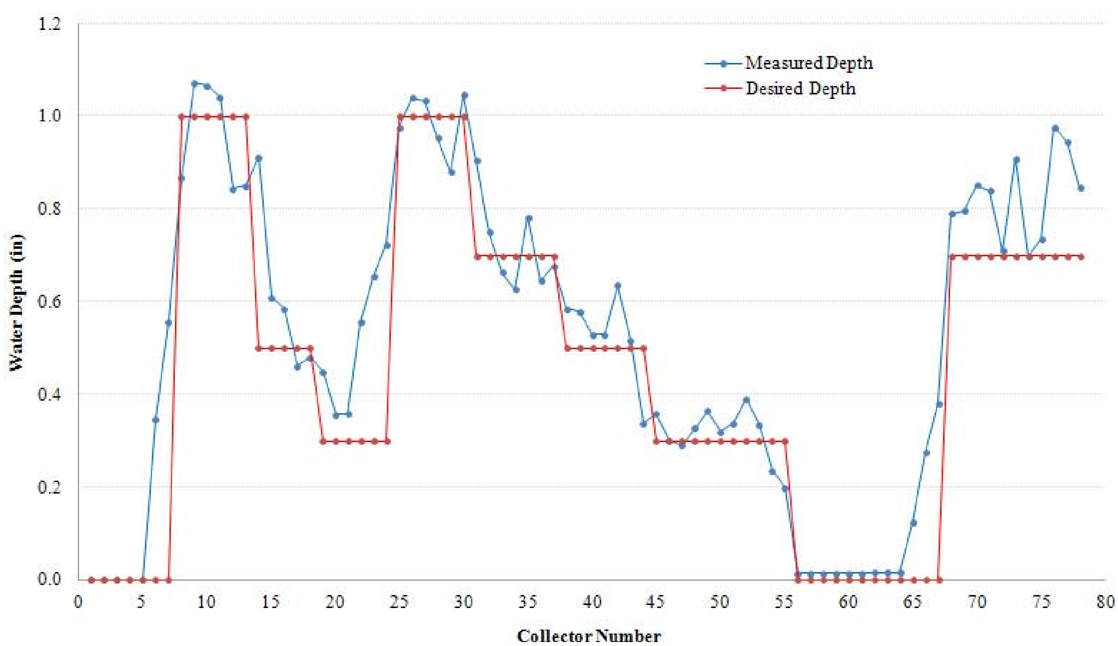

Figure 6. Desired water depth and measured water depth in the variable rate test.

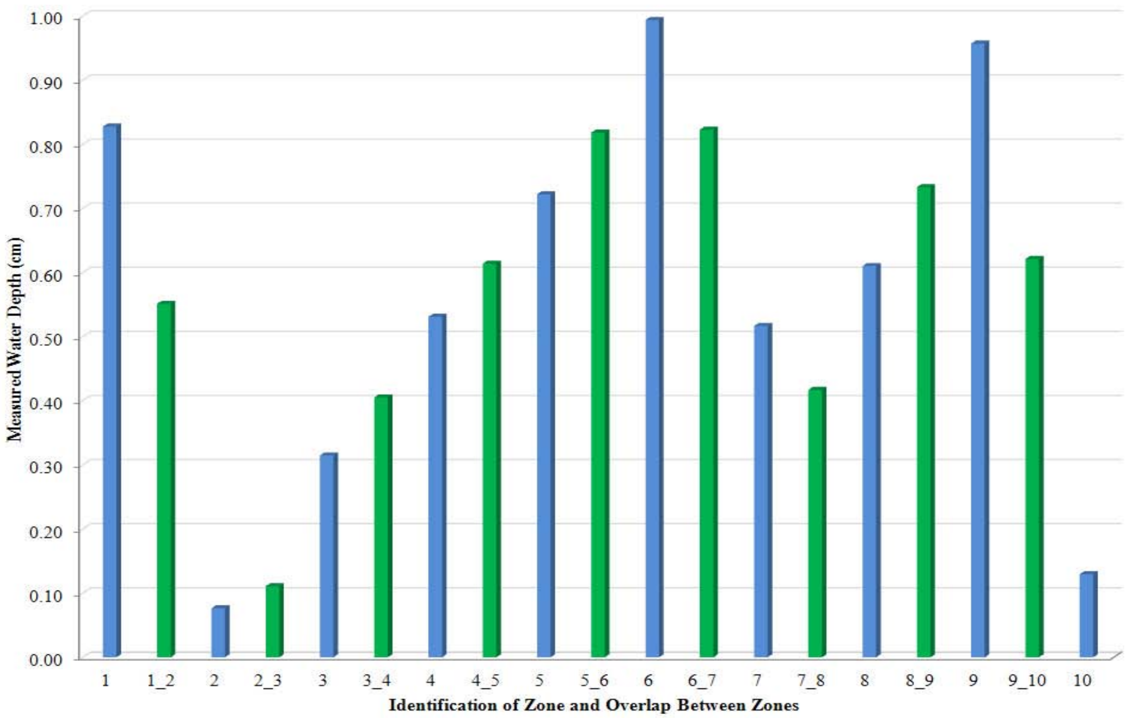

Figure 7. Applied water depth in control zones and in the overlap between control zones.

Automating Prescription Map Building for VRI Systems Using Plant Feedback

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Abstract. Prescription maps for commercial variable rate irrigation (VRI) equipment direct the irrigation rates for each sprinkler zone on a sprinkler lateral as the lateral moves across the field. Typically, these maps are manually uploaded at the beginning of the irrigation season; and the maps are based on prior yield, soil texture, topography, or soil electrical conductivity data. Producers are now beginning to make changes to their initial maps during the growing season based on visual observations, aerial imagery, and/or soil moisture sensors. In this study, plant feedback monitoring with infrared thermometers mounted on a moving sprinkler irrigation system was used to develop dynamic daily prescription maps for VRI sprinkler systems to aid in site-specific irrigation delivery. It was hypothesized that the plant feedback response can be used for site-specific control of crop water use efficiency. Here we discuss the application of a plant feedback algorithm combined with a variable rate irrigation system to implement site-specific irrigation management of sorghum throughout a growing season, and preliminary results to include examples of daily prescription maps, crop biophysical responses, and the average soil water content for the different irrigation treatments grouped by irrigation method. The methods used in this study provide one possible framework for establishing and integrating dynamic prescription maps into automatic control of irrigation scheduling.

Keywords: center pivot system, integrated CWSI, prescription maps, variable rate irrigation

Introduction. Commercial variable rate irrigation systems for zone control are designed to regulate flow to individual nozzles or banks of nozzles allowing for site-specific delivery of irrigation water along a pivot or linear move lateral as well as in the direction of sprinkler movement. A bank of nozzles under the control of a single solenoid valve is referred to as a zone. Prescription maps direct irrigation rates for each sprinkler zone on a sprinkler lateral as the lateral moves across the field. The initial irrigation patterns of VRI systems that are prescribed at the beginning of the growing season are manually uploaded at the beginning of the irrigation season, and can be based on, for example, one or more of the following: prior yield, soil texture, topography, rock outcrops, waterways and soil electrical conductivity information. Some producers are changing their initial maps during the growing season based on visual observations, aerial imagery, and/or soil moisture sensors (J. LaRue 2012, personal communication. It is problematic that these initial prescription maps are static for the irrigation season, which means that spatiotemporal variability of crop water stress throughout the growing season is disregarded.

One method to assess variability of crop water stress on a large scale and on a frequent basis is to use wireless sensor network systems to monitor crop canopy temperature and microclimatological parameters. Canopy temperature-based algorithms have been used to effectively control irrigation scheduling and crop water use efficiency. Two examples of thermal stress indices derived from canopy temperature are the Biologically-Identified Optimal Temperature Interactive Console (BIOTIC, Patent No. 5,539637; Upchurch et al., 1996) and the theoretical crop water stress index (CWSI) developed by Jackson et al., 1981. The BIOTIC method led to the time-temperature threshold (TTT) algorithm that has been used to automate irrigation for corn and soybeans using drip irrigation (Evett et al., 2000, 2006) and, using center pivot irrigation, soybeans (Peters and Evett, 2008), cotton (O'Shaughnessy and Evett, 2010), and forage sorghum (O'Shaughnessy et al., 2012a). A time-integrated CWSI algorithm was also used to successfully schedule irrigations for forage sorghum. Details of calculations for the upper (severely stressed) and lower (well-watered) limits of the CWSI are described in O'Shaughnessy et al. (2012b).

Both of these algorithms rely on a network of infrared thermometers to remotely monitor crop canopy temperature and were adapted for use with moving sprinkler systems by including a Global Positioning Sensor (GPS) on the lateral and integrating a scaling method (Peters and Evett, 2004) to estimate diel temperatures at remote locations using a one-time-of-day temperature reading at those locations and a reference diel temperature curve. If prescription maps can be constructed automatically based on spatiotemporal crop water stress data, then plant feedback algorithms for moving sprinkler systems can be integrated with commercial VRI systems. These daily prescription maps could direct site-specific irrigation according to crop water needs, which has the potential to improve crop water productivity and farm profitability by decreasing excessive irrigations, runoff, and deep percolation.

The goal of this study was to determine the feasibility of building dynamic prescription maps for a VRI equipped center pivot sprinkler system based on remotely monitored climatological and crop canopy temperature data. By imposing crop water stress using differing thresholds for irrigation scheduling, treatment plots with higher thresholds would receive irrigation signals less frequently than those plots with lower thresholds (Evett et al., 2002). This method would allow assessment of spatial and temporal crop water stress under the pivot field. Therefore, specific objectives were: (1) triggering irrigations for automatic treatment plots based on varying thresholds of an integrated CWSI; (2) developing a graphical user interface to integrate plant feedback with VRI hardware control to deliver irrigations when and where necessary; and (3) comparing crop biophysical and soil water measurements between scheduling methods (automatic and manual) across the same irrigation treatment level.

Materials and Methods

Experimental site and irrigation system

The experiment took place at the Conservation and Production Research Laboratory, Bushland, Texas [35° 11' N, 102° 06' W, 1141 m (3745 ft)] above mean sea level). The field soil was a Pullman clay loam, a fine, mixed, superactive, thermic, Torrertic Paleustoll (Soil Survey Staff, 2004). The field capacity (0.33 $m^3\ m^{-3}$; 4.0 in. ft^{-1}) and wilting point (0.18 $m^3\ m^{-3}$; 2.2 in. ft^{-1}) water contents were assumed uniform across the center pivot field. The climate is semi-arid with an average annual rainfall of 470 mm (18.5 in.). Early maturing sorghum, variety NC+5C35[1] was planted on June 27, 2012 (DOY 179) under an existing six-span center pivot system retrofitted with a variable rate irrigation (VRI) package (Valmont Industries, Valley, Nebr.). Irrigations were applied using low energy precision application (LEPA) drag socks (Lyle and Bordovsky, 1983) in every other furrow. Furrow dikes were placed in the furrows to reduce runoff and to provide the temporary detention required for LEPA irrigation in alternate furrows.

[1] The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

Nozzle sizes were selected to apply water as uniformly as possible along the lateral length. Irrigation application zones along the lateral were configured as banks of six sprinkler drop hoses. Each sprinkler drop hose was connected to a hydraulically actuated valve, and outfitted with a polyethylene weight and a pressure regulator rated at 41.4-kPa (6-psi). Each zone was controlled by an electronic solenoid valve at a pivot control tower. The solenoid valve activated all hydraulic valves in the zone. One-half of the center pivot field was cropped and divided into seven sectors of 22°. Treatment plots were established in a split plot block design (Littell et al., 2006) consisting of four concentric zones, each comprised of two sprinkler banks (12 drop hoses). A WAAS corrected GPS, with differential position accuracy of ± 3 m, communicated with the programmable logic controller of the pivot's VRI system using power line carrier communication. Irrigation methods (manual and automatic) were randomized radially and concentrically over half of the pivot field (Fig. 1).

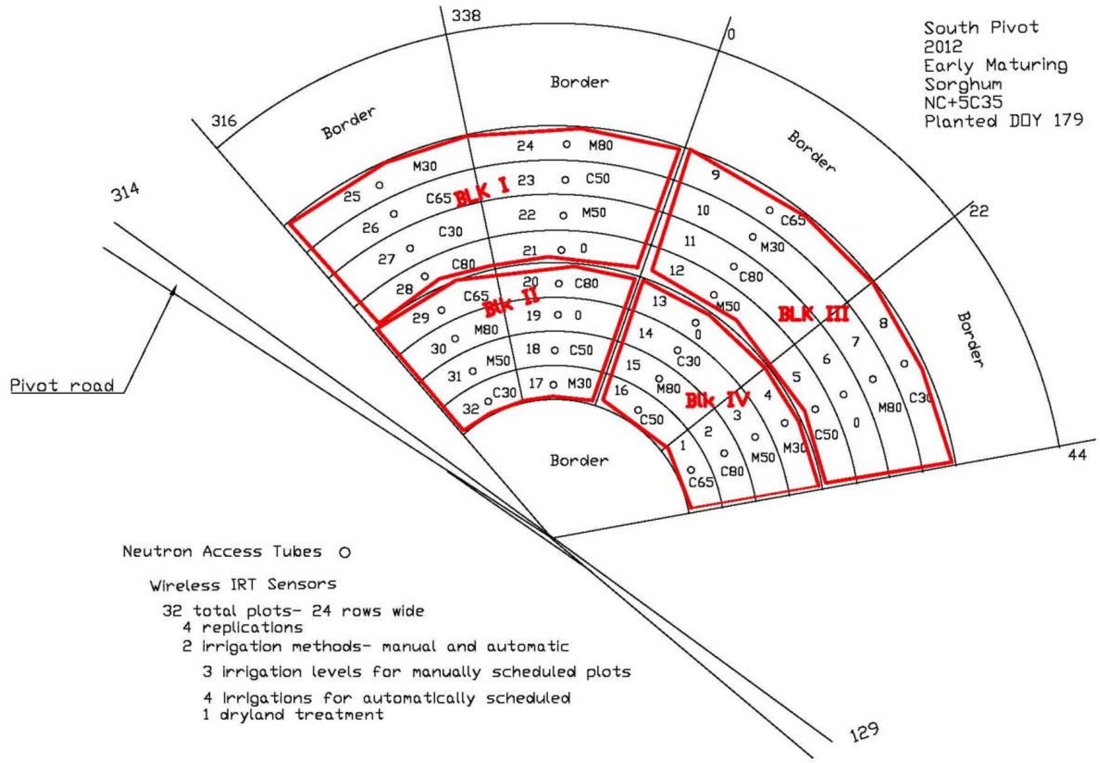

Figure1. Experimental field layout. The letter "M" in a plot indicates manual irrigation scheduling and the letter "C" in a plot indicates automatic irrigation scheduling using the integrated crop water stress index ($_i$CWSI).

Sensor Network Systems

A wireless sensor network (WSN) comprised of infrared thermometers was established on the pivot lateral and in the field below as described by O'Shaughnessy et al. (2012c). Sixteen sensors were mounted on masts hanging from the pivot lateral at the border of each concentric plot looking inwards at an oblique angle. The sensors viewed the cropped field forward of the irrigations. In addition, static "field" sensors were placed in 10 of the automatic irrigated plots (designated C80, C50, and C30) (fig.1) and two were placed in the manually scheduled M80 treatment plots to monitor well-watered canopy temperatures. Micrometeorological data (wind speed, relative humidity, air temperature and solar irradiance) were collected using a weather station located within the pivot field and transmitted hourly to the base station computer at the pivot.

Manual Irrigation Scheduling

Manual irrigations were scheduled over 3-4 days as needed in a 7-day period and based on 80%, 50%, and 30%, (designated $I_{80\%M}$, $I_{50\%M}$, and $I_{30\%M}$, respectively) of full replenishment of soil water depletion to field capacity in the top 1.5 m (4.9 ft) of soil. Soil water content was determined weekly using a neutron probe (NP) (model 503DR1.5, Instrotek (Campbell Pacific Nuclear), Martinez, Cal.) in 0.2-m increments from 0.10 m to 2.3 m (0.32 to 7.6 ft) in the $I_{80\%M}$ treatment plots. Access tubes were placed in a row in the center of each plot (24 rows wide). The neutron probe was field calibrated to accuracy of better than 0.01 m^3 m^{-3} (0.12 in. ft^{-1}), resulting in separate calibrations for three distinct soil layers, Ap, Bt and Btca, using methods described by Evett (2008). Irrigations for the manual and automatic control treatments were applied on the same day, over three days of the week if necessary. Any rainfall occurring prior to irrigation of the total amount for the week was subtracted from the required total.

Automatic Irrigation Scheduling

Irrigations in automatic control treatment plots were scheduled when pre-established threshold values were exceeded after the pivot scanned the field. Threshold values were 320, 380, and 450 for the automatic treatments corresponding to 80%, 50%, and 30% automatic control treatments and designated $I_{80\%C}$, $I_{50\%C}$, and $I_{30\%C}$. The integrated CWSI ($_i$CWSI) thresholds were calculated from canopy temperature and microclimatological data every minute over daylight hours for sorghum grown under a range of irrigation treatment levels at Bushland, Texas during the 2011 growing season (O'Shaughnessy et al., 2012a). In the case of extended cloud cover, irrigation was delivered to the automatic plots in the amounts of 80%, 50%, or 30% of 19 mm (0.76 in.) if estimated crop water use ($ET_c = K_c \times ET_o$) was greater than 0.76 inches. Percentages of the full amount were released to parallel the mechanism of irrigation threshold values, i.e. higher thresholds should result in less frequent irrigations and lessor amounts, while lower thresholds should result in more frequent irrigations or greater amounts. The full irrigation level and the threshold ET_c value for automatic treatments used on cloudy days was based on twice the peak daily crop water use rate of grain sorghum at the location (Steiner et al., 1991).

Crop coefficients (K_c) were from those established for Bushland, Texas as a function of accumulated growing degree days (AGDD) (Table 1) (Howell et al., 2008). Reference evapotranspiration (ET_o) was calculated from microclimatological data using the ASCE standardized reference evaporation equation (ASCE-EWRI, 2004). The GDD were calculated using GDD = $(T_{max} + T_{min})/2 - 10.0$°C where T_{max} and T_{min} are daily maximum and minimum air temperatures; and AGDD was the accumulated sum of daily GDD since emergence.

Table 1. Crop coefficients for sorghum grown in Bushland, Texas (Texas High Plains ET Network).

AGDD	Crop Coefficient (K_C)	General growth stage description
AGDD ≤ 265	= 0.10	Through emergence
265 < AGDD ≤ 615	= (0.0026 × AGDD) – 0.58	Through Flag leaf
615 < AGDD < 750	= 1.0	Boot to Flowering
AGDD ≥ 750	= -0.00043 × AGDD + 1.32	Soft dough to Black layer

The pivot scanned the field on even days of the year (DOY); these data were used to build a prescription map to deliver irrigations to manual and automatic plots on the odd DOY. The maximum application depth (VRI system keeping nozzles on continuously) of the irrigation system was set at 19 mm (0.76 in.) by setting the pivot travel speed at the end tower to 46.4 m hr-1 152.4 ft hr^{-1} ;9.2° hr^{-1}. Each time a treatment plot designated as 80% irrigation under automatic control received an irrigation signal, 0.76 inches was delivered, i.e. the pulsing rate to that particular plot was programmed at 100%. Irrigation rates for the other automatic treatment amounts were reduced from this according to the relative percentages (50 or 30%). Irrigation depths delivered to the manual designated plots were achieved by pulsing the appropriate banks at rates that were equivalent to 80%, 50%, and 30% of the entered application depth. The pulsing rate for each manual treatment plot was calculated using eq.1:

$$\text{Pulsing rate}_i = (\text{Manual amount}/0.76) \times I_{i\%M}\ (\%) \qquad \text{(Equation 1)}$$

where manual amount = amount entered in the graphical user interface (Fig. 2), and i = 80, 50, or 30 for the plots $I_{80\%M}$, $I_{50\%M}$, and $I_{30\%M}$, respectively. These amounts of irrigation also limited "washing-out" the furrow-dikes throughout the course of the irrigation season.

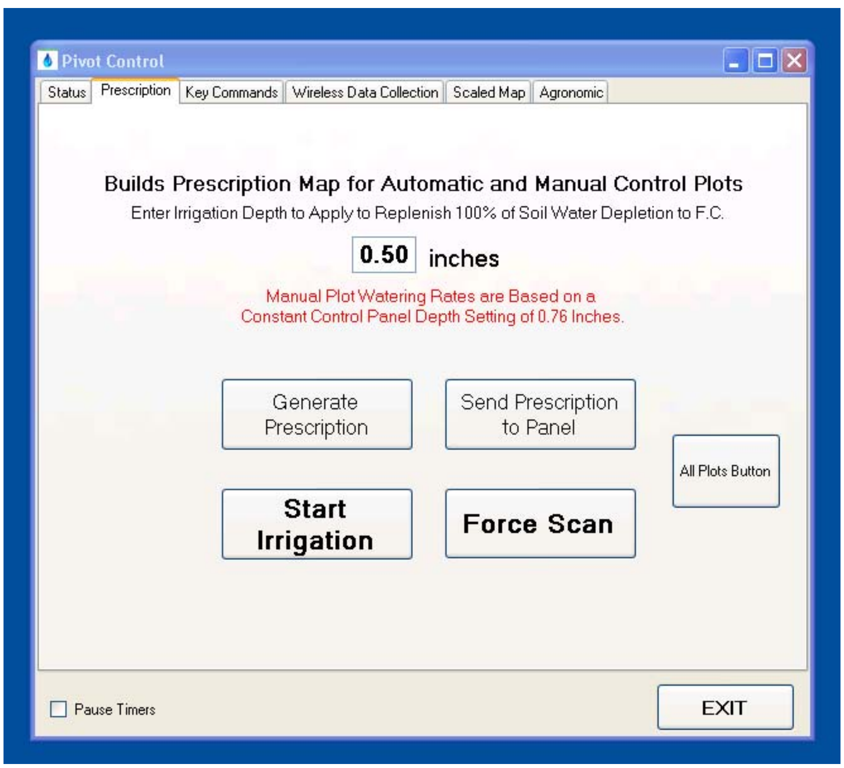

Figure 2. Graphical user interface constructed to deliver the appropriate irrigations depths to manual control plots (based on entered data) and exceeded thresholds for the automatic plots. The GUI uploads the prescription map to the pivot control panel and initiates irrigation when the respective buttons are pushed.

The prescription map was constructed using Visual Basic code. Treatment plot boundaries were static and defined by sectors and irrigation banks. Software previously developed by the USDA-Agricultural Research Service (ARS) was used to control the start and completion of irrigations, and recorded direction and speed of the pivot, angular location, and water pressure every minute. Plant height and width measurements were recorded approximately every 14 days throughout the growing season.

Statistical Analysis

Results from each year were analyzed separately using the Mixed Models procedure (Littell et al., 2006) with SAS statistical software (SAS 9.2, SAS Institute Inc., Cary, NC). The main factors of irrigation method (automatic and manual) and irrigation treatment (80%, 50%, 30%, 0%) were treated as fixed effects. Blocks were considered random effects. Differences among means of fixed effects were tested using least square mean differences and P values were adjusted for multiplicity with the least mean square difference student's t-test ($p < 0.05$).

Results

Results presented in this study were from data analyzed through DOY 255 when the sorghum was nearing the hard dough stage. On odd and even DOY, it was possible to consistently build a prescription map based on a mean calculated $_i$CWSI (Fig. 3a) specific to each automatic treatment plot, and information entered for irrigating manual treatment plots. The prescription maps were built using code specific to the commercial VRI software, and enabled a visual representation of spatial and temporal crop water stress throughout the irrigation season (Fig. 3b). The treatment plots where the thermal stress index was exceeded ($_i$CWSI value shown in red) indicated the location of a management zone where the crop was stressed. This resulted in an automatic decision to irrigate that particular zone. The decision was implemented by the generation and uploading of the prescription map to the pivot control panel. Irrigation of sectors outside of the 44° to 316° pie-shaped field were controlled by ARS software.

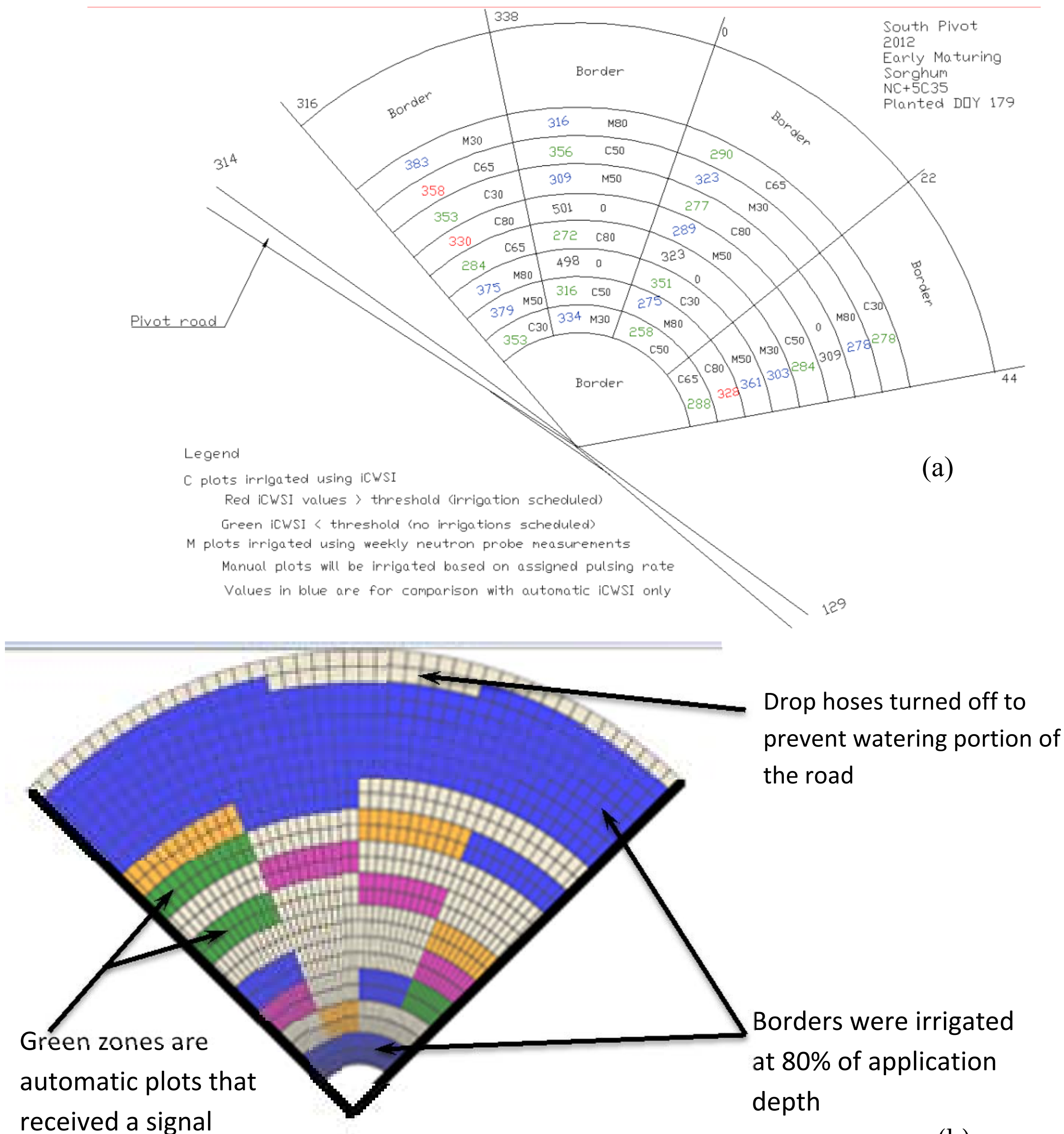

Figure 3. Examples of field treatment effects and treatment implementation illustrated respectively by: (a) integrated crop water stress index values ($_{i}$CWSI) calculated from field scan on DOY 254; and (b) prescription map built on DOY 255 based on $_{i}$CWSI values exceeding pre-established threshold values for treatment plots within sectors 44-316°.

Drought conditions prevailed in the 2012 growing season at Bushland, Texas, with total precipitation during the months of May through June amounting to 71.6 mm (2.82 in.), maximum daily temperatures averaging 31.6° C (89°F), and mean wind speeds of 4.1 m s^{-1} (9.15 mph) (Table 2).

Table 2. Climatological data for the 2012 growing season in Bushland, Texas, represented by monthly means of daily values.

Month	Min RH (%)	ET Ref mm	Max RH (%)	Min T (°C)	Max T (°C)	Precipitation (Total mm)	Wind speed (m s^{-1})	Max solar irradiance MJ m^{-2} d^{-1}
May	21.1	7.4	72.6	10.7	27.8	29	4.1	26.5
June	23.1	8.4	78.7	16.5	32.9	33	4.9	26.8
July	21.3	8.1	68.2	18.5	34.0	2	3.9	25.6
August	21.7	7.1	72.7	17.1	32.8	8	3.5	24.9

1 mm d^{-1} = 0.039 in. d^{-1}; 1°C = 1.8*(°C) + 32 in °F; 1 mm = 0.039 in.; 1 m s^{-1} = 2.24 mph; 1 MJ m^{-2} d^{-1} = 23.9 Langley d^{-1}.

Irrigation scheduling began on July 30, 2012 (DOY 211) and will continue until the grain reaches physiological maturity, which is expected to occur in 2-3 weeks. As of September 11, 2012 (DOY 255), the total amount of irrigation applied to manual treatment plots ($I_{80\%M}$, $I_{50\%M}$, and $I_{30\%M}$) was 361, 226, and 137 mm (14.2, 8.9, and 5.4 in.), respectively. Average irrigation amounts applied to the automatic control plots ($I_{80\%C}$, $I_{50\%C}$, and $I_{30\%C}$) were 279.4 ± 33, 218 ± 38.1, 173 ± 46 (11.0 ± 1.3, 8.6 ± 1.5, and 6.8 ± 1.8 in.), respectively. On DOY 254, the mean soil water content for the $I_{80\%M}$ treatment plots was 0.27 m^3 m^{-3} (3.2 in. ft^{-1}) and that for the $I_{80\%C}$ plots was 0.26 m^3 m^{-3} (3.1 in. ft^{-1}). The differences in irrigation amounts applied to the $I_{80\%M}$ and $I_{80\%C}$ plots produced observable differences in plant height that were significantly different (Table 3). However, irrigation amounts and plant heights were not significantly different at the 50% and 30% irrigation levels when compared across irrigation methods.

Table 3. Statistical comparison of plant height and cumulative irrigations through DOY 255 for grain sorghum for the 2012 growing season in Bushland, Texas. Values followed by the same letter in each column and grouped by effect, are not significantly different.

	Plant Height (cm/in)	Cumulative Irrigations (mm/in)
Irrigation Method		
Manual	93.2/36.7a	241/9.5a
Auto	88.6/34.9a	224/8.8a
	F=5.0, p =0.04	F= 2.89, p = 0.11
Irrigation Level		
$I_{80\%}$	100.0/39.4a	320/12.6a
$I_{50\%}$	86.6/34.1b	221/8.7b
$I_{30\%}$	82.0/32.3b	130/5.1c
$I_{0\%}$	66.6/26.2c	0/0d
	F=17.8, p <0.0001	F=87.9, p < 0.0001
Irrigation Method × Irrigation Level		
$I_{80\%M}$	106.9/42.1a	361/14.2a
$I_{80\%C}$	93.7/36.9b	279/11.0b
$I_{50\%M}$	89.4/35.2bc	226/8.9c
$I_{50\%C}$	83.6/32.9cd	218/8.6c
$I_{30\%M}$	81.5/32.1d	137/5.4d
$I_{30\%C}$	83.1/32.7bcd	142/5.6d
	F=2.7, p=0.09	F=11.1, p=0.001

Mean seasonal $_{i}$CWSI values calculated through DOY 254 (Table 4) grouped by irrigation level, compared well between irrigation methods. The average stress index values for the 50% and 30% treatment levels were lower than the threshold values, but in agreement between scheduling methods. This was likely due to soil background making surface temperatures read cooler immediately after irrigation from wet soil, and increasing surface temperatures when drier.

Table 4. Mean seasonal integrated crop water stress index values calculated for each irrigation treatment and method through DOY 254, 2012.

Irrigation Treatment Amount	Irrigation Method		
	Manual	Automatic	Threshold
80	324.4	322.9	320
50	342.2	344.1	380
30	391.4	393.5	450
0	468.8		

Conclusion and Discussion

In this study, prescription maps were based on the previous 24 hours of data. Preliminary results suggest that automatic irrigation scheduling using plant feedback methods can be integrated with VRI hardware and software to construct dynamic prescription maps and control crop water use efficiency. If the lesser irrigation amounts delivered to the $I_{80\%C}$ irrigation plots result in significantly reduced yields or water use efficiency values, the threshold can be reduced to increase the frequency of irrigations. In previous sorghum studies without VRI, however, the same threshold $_{i}$CWSI value used for the $I_{80\%C}$ treatment did not result in significantly different yields than did the corresponding manual irrigation treatment ($I_{80\%M}$).

This study demonstrates the ability to integrate sensor feedback with VRI equipment to assess spatiotemporal variability with greater frequency than weekly manual soil water readings. At harvest, grain yield and water use efficiency will be calculated from hand-samples to assess the overall effectiveness of using plant feedback methods for irrigation scheduling and controlling water use efficiency for forage sorghum.

The methods used in this study provide one possible framework for establishing and integrating dynamic prescription maps into automatic control of irrigation scheduling. In this study, spatiotemporal crop water stress was induced by establishing variable thresholds for irrigation scheduling. Irrigation management zones were established by defining the borders of each treatment plot by sector and sprinkler irrigation bank. A second fundamental element was to assess, on a regular basis, the performance of the crop in a management zone against a pre-defined performance index (i.e. a stress index threshold value). The third fundamental element was the implementation of a secondary decision support system to estimate crop water use to control irrigations in the case of extended periods of cloudy days with no precipitation. Future work will require correcting radiometric temperature measurements for cases in which the crop canopy is less than full, and the incorporation of other sensor network systems such as soil water sensors to overcome issues of inadequate temporal frequency due to the time it takes the pivot to move across the field.

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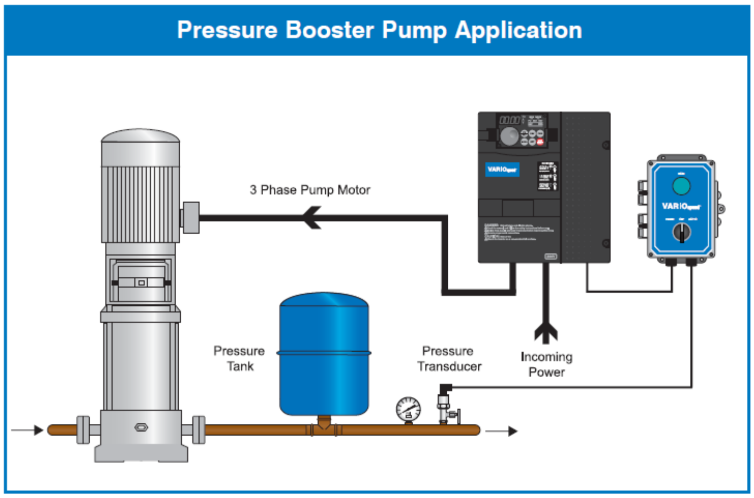
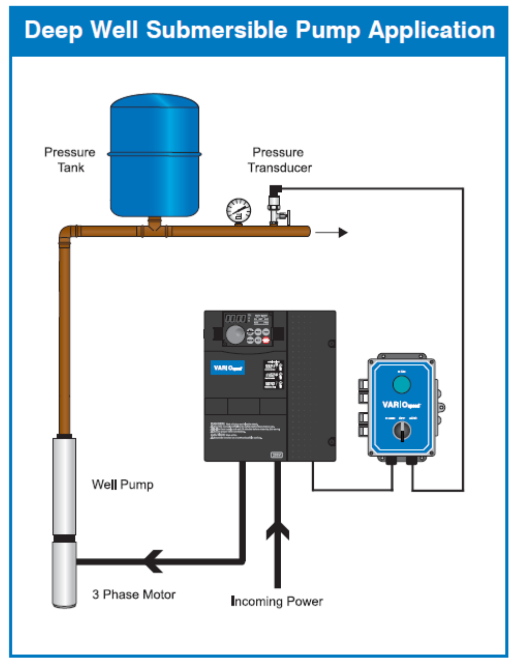
Advanced Pump Control for Irrigation Applications





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Executive Summary

In this world of ever advancing technologies, the water and waste water pumping industry has seen an explosion in the use of highly technical variable frequency drives, or "VFD's". Known by many generic names, and produced by many manufacturers, these technical marvels have advanced to provide endless possibilities, for ways in which a liquid pump and motor can be controlled. This expansion of possibilities has opened up many methods that can be used in controlling the discharge pressure in a pumping system.

This paper is intended to sort out the main methods for controlling pressure in a water/wastewater application, and in doing so will also discuss the primary, and advanced methods of pump, motor, and piping protection. A side benefit of VFD's is that the operator is also able to monitor system status and ongoing electric power consumption. Undetected inefficiencies can significantly increase utility bills, that when added among many systems can cripple the owner's maintenance budget or utilities managing many systems.

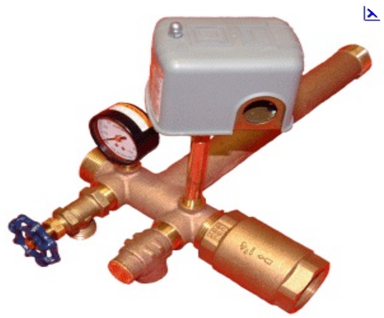
Controlling Pressure

The common components for controlling pressure in a pump system include:

- Manual Pressure Switch
- "PRV" Pressure Reducing Valve
- Pressure Transducer

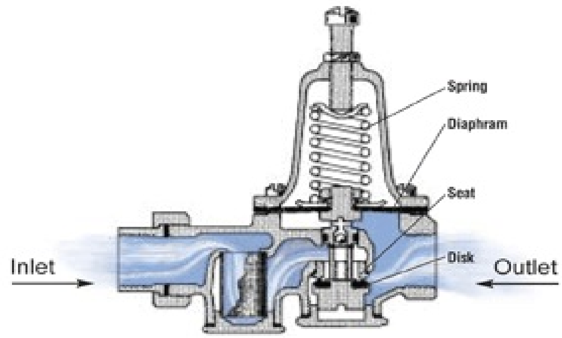
Manual Pressure Switch

This method has been the mainstay of liquid pressure systems for many years. It has served the industry well and remains the pressure controlling method for a large percentage of systems. Systems utilizing this method will experience pressure increase and decrease from start to stop points based on pressure in their system, or will need to substantially increase the pressure tank in the system in order to decrease the pressure differential and still maintain the minimum run time required by pumps.



"PRV" Pressure Reducing Valve

There are two categories of PRV used in systems, depending on location and application. For municipal systems, the incoming water to a residence or business is considerably higher than needed. This is intentionally done to allow for variations due to elevation, demand fluctuations, and fire suppression requirements that typically come off of the same municipal system. The PRV in this case eliminates or mostly eliminates pressure variations by simply stopping excess water from



flowing beyond the PRV. From an energy consumption point of view, this is an acceptable method given that pressure must be constant within one system throughout a whole community where there are huge variations in volume and pressure needs.

A second PRV method employed for systems, is commonly referred to as a cycle stop valve or CSV. These units are designed to limit the maximum pressure in a system by restricting the output through the valve based on the pressure on the output side similar to more common PRV's. CSV's also do two more things. When the pump turns on at the low pressure switch point, the valve causes the buildup of pressure to a desired point between the low and high and then reduces the output volume by restricting it to only the amount required to maintain the desired point while also maintaining a minimum amount of flow to prevent damage to the pump. When usage shuts off completely and the set pressure is reached, the valve then diverts the flow through a bypass to the pressure tank to restore the backup capacity. This method maintains a constant pressure for a time, however allowing the pump to run at maximum head conditions and restricting the flow to this degree, greatly reduces the running efficiency of the pump.

Pressure Transducer

The pressure transducer acts simply as an information source. This information is provided typically to a variable frequency drive or VFD. The VFD is able to use this information to control the amount of energy sent to a motor/pump and slow down or speed up the pump to maintain a constant pressure. This is done by changing the frequency of the electrical pulses through what is known as an inverter. This allows for full control of the output of the system. Coupled with a modestly priced VFD the user is also able to monitor and subsequently protect the system from damage.

The Historical Problem

Water pressure systems historically included a pump/motor with capacitor starter, controlled by a simple pressure switch that would turn on the pump when the pressure in the system dropped below a pre-determined “start” point, and turn off the pump when the same switch would open back up. The differential between the “start” and “stop” points and the size of the pressure tank attached to the system, determined the run time of the pump. To avoid excessive “cycling” of the pump, the pressure tank was sized to allow for the minimum run time required, based on the manufacturer’s recommendation to ensure long life of the pump/motor combination and to maintain the warranty.

Problems occur when the operating conditions of the system change. The following are variables that, when changed, affect the system’s ability to maintain intended results.

- Demand on the system changes
- The supply reservoir cannot replenish itself at the rate required
- A broken line in the system
- The pump/motor begins to fail
- A foreign object gets lodged in the pump

Without a method of detecting these conditions, the system continues to run; causing physical damage to pumping equipment and potentially causing substantial physical damage beyond the system itself. Even before noticeable external damage, substantial increases in electricity usage results from most of these conditions, when not detected promptly.

The Solution

A properly sized variable frequency drive, motor and pump, coupled with a pressure transducer, provides for; a constant pressure within the pumping range, maximum energy efficiency for the given system, and peace of mind knowing the drive is monitoring the system, shutting it down to protect it, other equipment in the system, and external physical damage in the area. Let's look at each of these benefits in more detail.

Consistent Performance

Society has come to expect that when they turn on the faucet, the water will flow at the same rate and pressure regardless of how many people are using the system at one time. The VFD is best suited to provide this "variable" rate and still maintain an efficiently running system. Without getting too technical, the drive does this by reproducing the AC sine wave at a variable frequency. This frees us from the limitations given by the electrical utility that typically provides electricity at sixty pulses per second or 60 hz. Historically motors were designed to run most efficient at this speed; however new electric motors, windings and insulating material, are designed specifically to take advantage of this ability. These motors are "inverter duty rated". By changing how fast the pulses are fed to the motor, the output of the pump can be controlled variably without restricting the flow and reducing efficiency of the pump.

Maximum efficiency

Getting a constant pressure by controlling the electrical energy sent to the motor, rather than restricting the output of the liquid, VFD's are able to gain efficiency over other methods, and reduce the utility cost of the system.

Monitoring, Protecting, and Notifying

The monitoring abilities provided by modern VFDs, are only limited by the imagination of the designer and the ways in which the system is intended to be used and protected from damage. The most commonly used protections in water pressure applications are discussed below.

System Pressure

Basic to water systems, the pressure of the water is monitored constantly. This information is used in many ways to determine the health of the overall system.

Low/No Flow (also known as dry run)

When the system is properly installed, the normal operating speed will be established that determines how fast the motor needs to run to maintain the system or “set pressure”. If the system is not maintaining the pressure required within the normal speed range, it assumes there is not enough water and will stop running to protect the pump from “dry running”

Seal Fail

This protection requires a pump motor equipped with a sensor that can detect when a seal on the motor has failed and there is water getting into the motor. Typically used in larger systems, this notifies the user that maintenance is required to restore the system to health.

Motor Overload Protection

By setting the maximum amperage based on the nameplate, the motor is not damaged by over-current. Branch circuit protection is still provided by the breakers required by local code. Advanced functions available in most modern drives, allows that the drive will not only shut down on over-current, but will also report by error code when the condition occurred. This is very helpful when diagnosing the root cause of the failure; during startup, running, or deceleration.

Under-voltage

Damage to the motor is prevented should there be a brownout or other under voltage condition on the input line power.

Three Phase Power Issues

In three phase systems, the VFD protects the drive and motor, should an unexpected phase loss occur in the incoming power supply. Parameters can also be set to protect from an un-acceptable amount of phase imbalance. These measurements are on the incoming side of the VFD, and depending on how the drive is sized; a larger amount of error can be tolerated, without affecting the output of the drive to the motor. In fact, many drives are used just for this purpose. Running a 3 phase motor, where 3 phase power is not available, drives can be sized and setup to convert single phase incoming power to three phase output (motor) power.

Self Protection

In addition to the advanced protections for the pump, motor and piping system, modern VFD's have a multitude of protections built into the drive to protect itself from being damaged, provided it was installed and setup properly to match the other components in the system.

Notification of Protections

All these represent a large advancement in protecting your pump, motor and piping; however does nothing to notify you if the system is shut down as a result of one of these protection faults. If your system is critical, you will want to consider adding a remote monitoring or notification module. These systems are as simple or advanced as needed to match the desired notification level. Full "SCADA" (Supervisory Control And Data Acquisition) systems are quite advanced, used typically in large scale systems, and can add a large expense to the initial and monthly expense of operating the system.

For most irrigation, well pumping, and pressure boosting systems, an economical add-on that offers a cell phone based notification when faults occur, can add peace of mind when the system is in an area not checked frequently to prevent physical damage should the system shut down.

No shortcut for good design

While modern VFD's provide a much higher level of monitoring and protection for your system, drives cannot make up for a poorly selected motor and pump combination. Solid system design and an up-front investment is money well spent when installing a pressure controlled water system. One of the most common issues blamed on VFD systems is asking a constant pressure system to operate on the flat portion of the pump curve. If the requirements of the system will operate the motor at the top 15-20% of the frequency available, there is little range left to allow for a variable flow. If your system operates satisfactory at 60hz yet is at no flow (dead head) at 50-55hz. your system is prone to issues in the future. This condition gives the variable frequency drive an unwarranted bad name when the real issue is in the design of the pumping system itself. There is no substitute to having a good, well designed setup by a reputable company with experience with these types of systems.

Summary

The large supply of VFD's from a variety of manufacturers, and the ever advancing technology built into them, is proof in and of itself that this technology makes sense for advancing the reliability and protections available to systems in this market. It also lends well to the "smart grid" technology and connectivity necessary to monitor and control energy usage throughout the life cycle of a pumping system. The use of variable frequency drives in this market has now gone beyond critical mass and its future use in this market will continue to increase. PN

Infiltration Characteristics of Bare Soil under Sequential Water Application Events

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Abstract. *The marked reduction in infiltration rate caused by formation of a soil surface seal is a well known phenomenon but often ignored in infiltration models. The effect sequential water application events have on infiltration rate and soil surface seal formation has rarely been investigated. The objective of this study was to investigate the effect sequential water application events have on the infiltration rate of a Portneuf silt loam soil with and without water droplet impact. The Portneuf silt loam soil developed a soil surface seal that reduced infiltration rate both with and without droplet impact on the bare soil surface. When the soil surface was protected during the first rainfall event, drying the soil did not increase infiltration rate for subsequent rainfall events when the soil surface was protected, but drying did increase infiltration when the soil was unprotected in the first rainfall event. Final infiltration rate was inversely related to specific power of the simulated rainfall. Either with or without water droplet impact, final infiltration rate for the Portneuf silt loam soil decreased to less than 20 mm hr^{-1} within three rainfall events. Given that the Portneuf silt loam soil is extremely vulnerable to surface seal development with little difference in final infiltration rate, irrigation time must be maximized and peak application rate minimized in order to maximize infiltration depth. These requirements combined with the operating characteristics of center pivot irrigation systems means that sprinklers with maximum wetted diameter need to be selected in order to maximize infiltrated depth.*

Keywords. Sprinkler irrigation, Center pivot, Infiltration, Runoff, Soil surface seal, Droplet kinetic energy.

Introduction

The marked reduction in water infiltration rate of bare soils caused by raindrop impact has been recognized for over a century and has been extensively documented and studied over the past 70 years. The decrease in water infiltration rate of soils under droplet impact was first investigated by Duley (1939), Borst and Woodburn (1942), and Ellison (1945). McIntyre (1958) was the first to measure saturated hydraulic conductivity of soil surface seals created by raindrop impact. He found that the saturated hydraulic conductivity of the formed seals was a function of the soil, applied water depth and application rate. Seal saturated hydraulic conductivity was found to be 2 to 3 orders of magnitude less than for the underlying soil. Moldenhauer and Long (1964) found that infiltration rate was a function of soil properties, kinetic energy of the water drops and application intensity. They found that time for runoff to begin was a function of cumulative kinetic energy applied to the soil. Studies of Edwards (1967), Mannering (1967), Sharma (1980), Baumhardt (1985), Mahamad (1985), Thompson and James (1985), Betzalel et al. (1995) have demonstrated the influence droplet kinetic energy and water application rate has on infiltration rate into bare soils.

Nearly all of the research related to 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; Silva, 2006). Soil surface seal formation in combination with high water application rates under center pivot sprinkler irrigation exacerbates potential runoff and erosion hazard. Runoff under center pivot sprinkler irrigation is a well recognized problem (Undersander et al., 1985; DeBoer et al., 1992; Hasheminia, 1994; Ben-Hur et al., 1995, Silva, 2006), but is normally unseen because runoff often infiltrates before exiting the field boundary as only a small fraction of the field is irrigated (saturated) at a given time and/or runoff collects in low spots within the field.

Studies' documenting the significant effect water droplet impact has on the infiltration rate of bare soils led to the development of empirical models representing the transient nature of the saturated hydraulic conductivity of soil surface seals during a rainfall event. In general, these models expressed hydraulic resistance or saturated conductivity of the seal layer as an exponential decay function of time or applied droplet kinetic energy (Farrell and Larsen (1972); van Doren and Allmaras (1978); Linden (1979); Moore, et al. (1981); Brakensiek and Rawls (1983); Bosch and Onstad (1988); Baumhardt et al. (1990)). These models all include three or more parameters that need to be estimated from simulated rainfall infiltration experiments. These parameters have not been related to bulk soil properties to expand the models to other soils in general with the exception of Brakesiek and Rawls (1983) who developed a crust factor to account for crusted soil infiltration with the Green and Ampt (1911) infiltration model.

Despite nearly 70 years of research on the reduction of water infiltration rate of bare soils caused by raindrop impact, nearly all studies have been limited to a single water application event. Little is known about how infiltration rate changes under sequential water application events of raindrop impact on bare soil. The objective of this study was to investigate changes in water infiltration rate under sequential water application events with different water droplet kinetic energies and water application rates.

Methods and Materials

Laboratory rainfall simulator tests were conducted on a Portneuf silt loam soil with particle size fractions of 14% sand, 65% silt and 21% clay determined using hydrometer method. Rainfall was simulated on the soil packed in a box measuring 0.3 m wide, 0.45 m deep and 1.0 m long placed on 5% slope. The soil was air dried, sieved and packed to a bulk density of 1.3 to 1.4 Mg m^{-1}. The rainfall simulator produced droplets with kinetic energies per unit volume of 3.9 and 8.5 J m^{-2} mm^{-1} using fall heights of 0.3 and 1.0 m, respectively. Zero kinetic energy water application was simulated by placing an evaporative cooler pad over a screen with 7.6 mm square opening suspended 20 mm above the soil surface. Water application rates ranged from 90 to 120 mm h^{-1}. Rainfall simulation duration ranged from 30 to 60 min. Runoff volume was measured by continuously recording the cumulative weight of runoff water. Total infiltrated volume was determined by weighing the soil box immediately before and after rainfall simulation. Water application rate was calculated by dividing the sum of infiltrated and runoff volumes by time of application. Infiltration rate was calculated as the difference between water application rate and runoff rate, neglecting soil surface storage.

The soil was dried between water application events by placing the runoff box in a walk-in forced air drying room with a temperature of 60 ºC for 5 to 10 days. Soil moisture in the top 20 cm of soil was measured with TDR (TDR 100, Campbell Scientific, Inc. Logan, UT)

Specific power (W m^{-2}) also termed kinetic energy flux density (Thompson and James, 1985) can be calculated for a rainfall simulator with constant application rate and drop kinetic energy as:

$$SP = \frac{KE_d \cdot R}{3600} \quad (1)$$

where KE_d is droplet kinetic energy per unit volume (J m^{-2} mm^{-1}) and R is application rate (mm hr^{-1}).

Results and Discussion

Infiltration rate for the Portneuf silt loam soil under zero specific power (protected soil surface) with two sequential (fig. 1A) and three sequential (fig. 1B) rainfall events indicates that infiltration rate decreases after the first rainfall event even in the absence of raindrop impact. Final infiltration rate was approximately 38 mm hr^{-1} for the first application event and approximately 20 mm hr^{-1} for subsequent application events. Reduced infiltration rate with subsequent water application events suggests the formation of a soil surface seal without raindrop impact. Physical (nonbiological) soil surface seals can be caused by a number of physical processes. Soil surface seals result from deposition of dispersed soil particles within soil surface pores which subsequently clog pores creating a low permeability layer at the soil surface (Assouline, 2004). Most commonly, the presence of dispersed soil particles is due to the breakdown of soil aggregates by raindrop impacts and/or slaking processes but can be due to deposition of dispersed soil particles carried by overland flow. Soil surface seals are generally classified as either structural or sedimentary features (Neave and Rayburg;, 2007; Assouline, 2004). Structural seals form in association with raindrop impact on bare soils while sedimentary seals result from lateral redistribution of sediment by runoff or wind and does not require direct soil impact by rainfall (Neave and Rayburg; 2007). The apparent soil surface seal leading to a reduction in infiltration rate for the second and third rainfall events with zero specific power on the Portneuf silt loam soil are sedimentary in nature. Since the soil surface is completely protected, the source of soil particles forming the surface seal are from slaking of soil surface aggregates under saturated conditions, which are subsequently redistributed by runoff. Soil aggregate structure is greatly reduced when soil water approaches saturation (Francis and Cruse 1983). Under unsaturated soil surface conditions (no runoff) surface aggregate strength would be greater and soil surface seal development would likely be reduced or absent. Further research is necessary to investigate this aspect.

To investigate the influence of droplet impact on soil surface seal development and infiltration rate of the Portneuf silt loam soil, two separate tests with simulated rainfall with specific power levels of 0.12 W m^{-2} and 0.27 W m^{-2} were applied followed by zero specific power water application after the soil had dried, figures 2A and 2B, respectively. For the first rainfall event with 0.12 W m^{-2} specific power applied final infiltration rate was approximately 33 mm hr^{-1} and for a first rainfall event with specific power of 0.27 W m^{-2} the final infiltration rate was approximately 8 mm hr^{-1}. The higher specific power greatly reduced final infiltration rate. In both tests, infiltration rate at the end of the second zero specific power water application event was higher than at the end of the first rainfall event when drops impacted the soil surface. This indicates that the effect of the soil surface seal on infiltration was reduced by drying. The soil surface cracked when dried which apparently fractured the soil surface seal, increasing infiltration rate. This is in contrast to the situation where zero specific power was applied with multiple water application events and infiltration rate was lower for the second water application event (figs. 1A and 1B). With zero specific power water application, drying the soil surface did not increase infiltration rate. Apparently, the soil surface seal formed under zero specific power is more permanent than that developed under water droplet impact.

Infiltration rate of the Portneuf silt loam soil under multiple rainfall events with a specific power of 0.25 W m^{-2} (fig. 3) decreases rapidly to and returns to a relatively low final rate of approximately 12 mm hr^{-1} during each subsequent application event. Even though the soil was dried between rainfall events, drying had little effect on infiltration rate after 10 minutes with nearly the same infiltration rate at the end of each rainfall event. Apparently, cracking of the soil surface with drying had little lasting effect

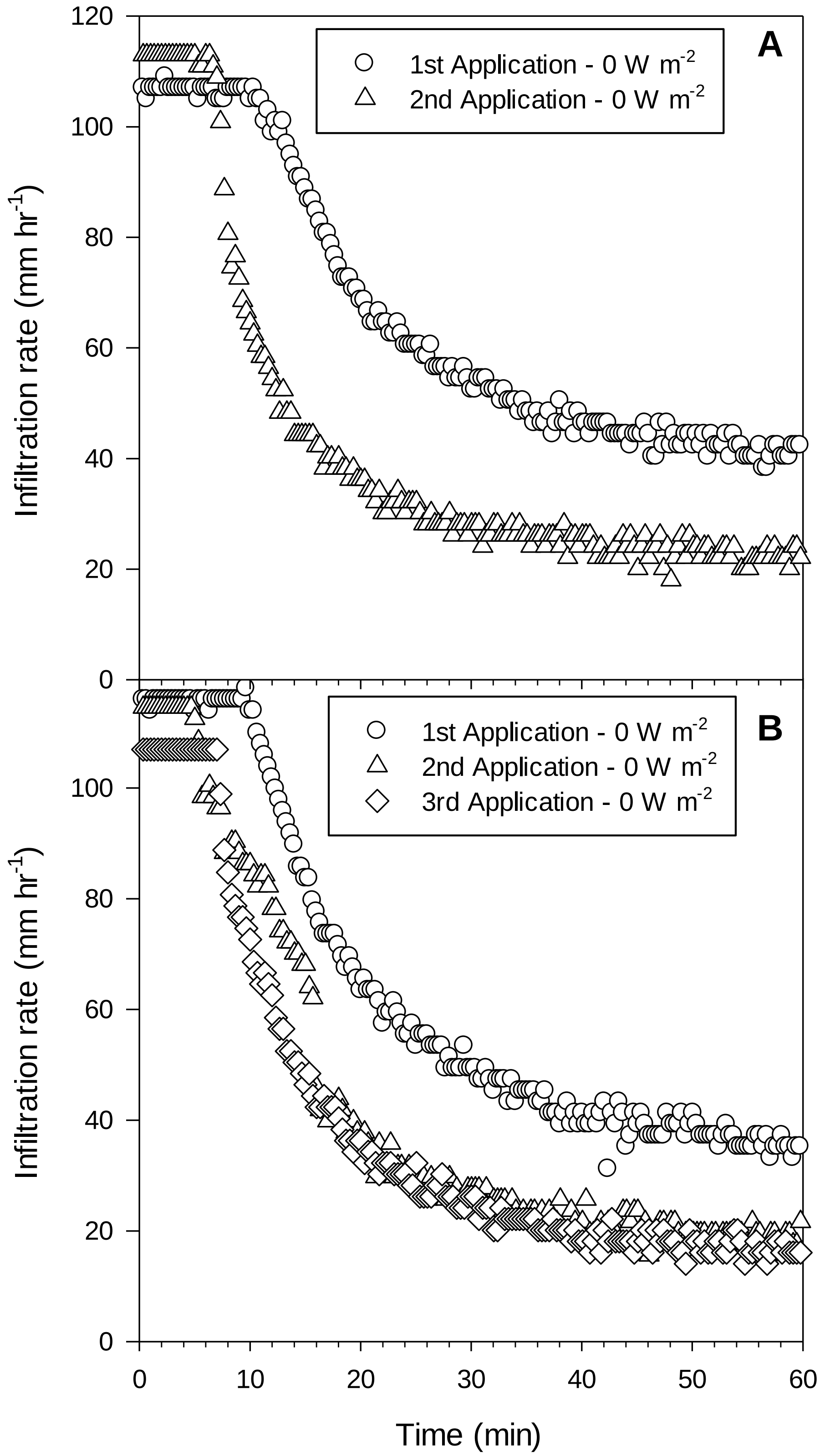

Figure 1. Infiltration rate of Portneuf silt loam soil under two (A) and three (B) sequential simulated rainfall events with zero specific power (soil surface protected).

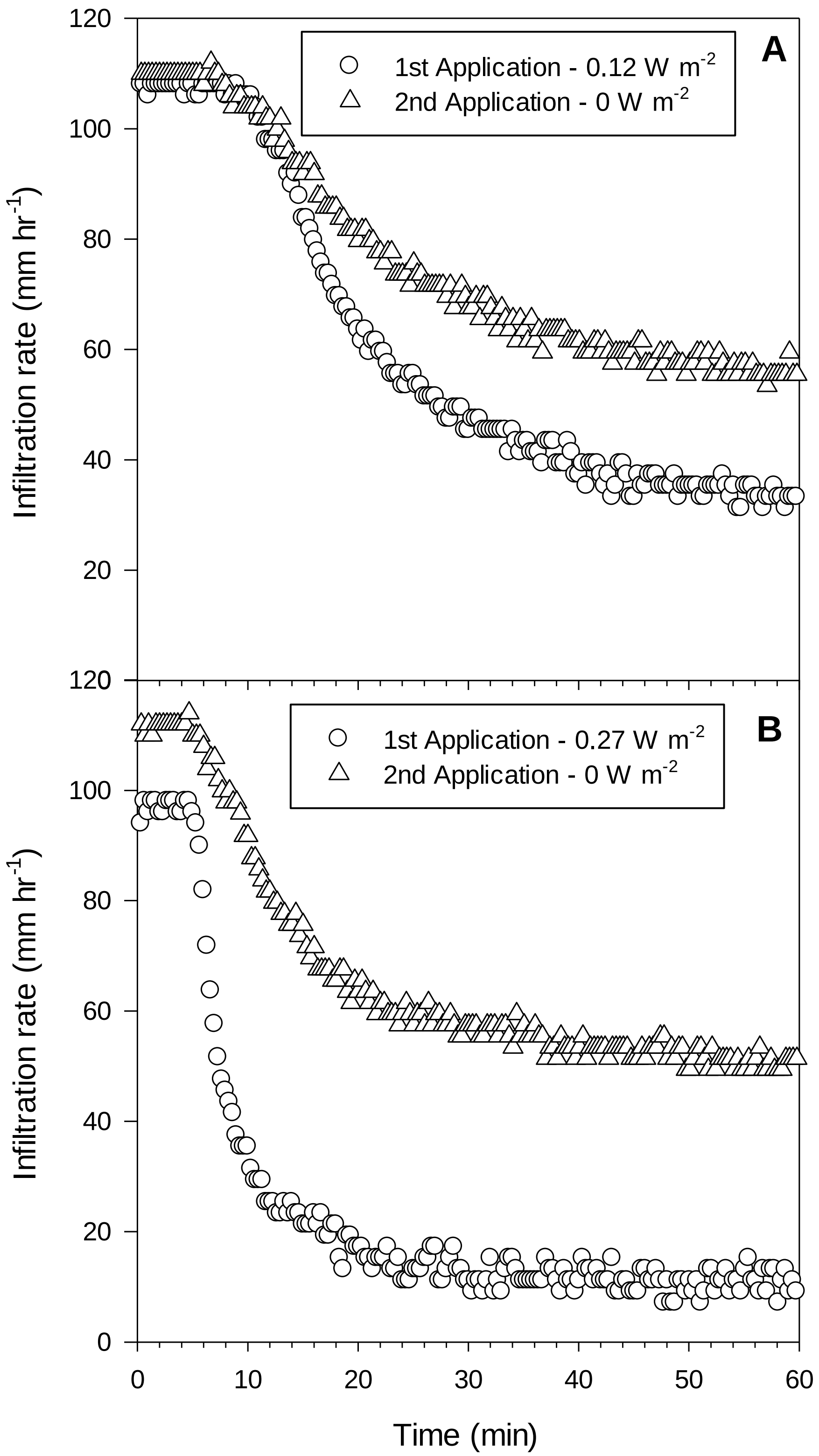

Figure 2. Infiltration rate of Portneuf silt loam for sequential simulated rainfall events of 0.12 W m^{-2} specific power on bare soil followed by protected soil surface (A) and 0.27 W m^{-2} specific power on bare soil followed by protected soil surface (B).

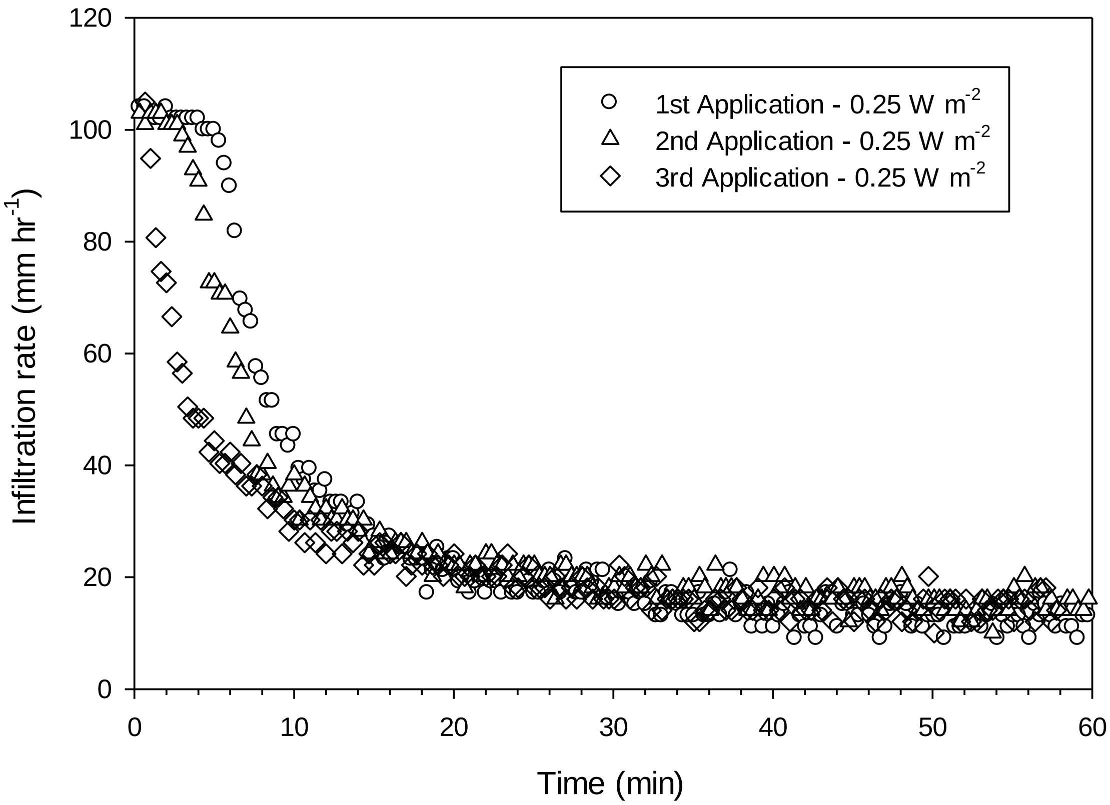

Figure 3. Infiltration rate of Portneuf silt loam soil for three sequential simulated rainfall events on bare soil with 0.25 W m^{-2} of specific power.

when water droplets impacted the bare soil surface. The time to runoff decreased with each simulated rainfall event (fig. 3) indicating an additive effect to how rapidly the soil surface seal developed with each subsequent rainfall event. The final filtration rate did not continue to decrease with each subsequent rainfall event, which is a common assumption. The final infiltration rate appears to be inversely related to specific power with greater specific power resulting in lower final infiltration rate.

For the Portneuf silt loam soil used in this study, the results indicate a soil surface seal that reduces infiltration rate will develop with sequential water application regardless of whether or not droplets impact the bare soil surface. Drying the soil increased infiltration rate for subsequent water application without droplet impact (zero specific power), but had no effect on infiltration rate for subsequent water application with droplet impact. Either with or without water droplet impact, final infiltration rate for the Portneuf silt loam soil decreased to less than 20 mm hr^{-1} within three rainfall events. This result is similar to that of Neave and Rayburg (2007) who found no significant difference in runoff between protected and bare soil conditions under sequential simulated rainfall on a sandy loam soil. The implication for center pivot sprinkler irrigation on a Portneuf silt loam soil is that infiltration rate will decrease to less than 20 mm hr^{-1} regardless of the degree of soil surface cover. The final infiltration rate will depend upon the specific power of the sprinkler used. Given that a soil surface seal is going to develop with little difference in infiltration rate, irrigation time must be maximized and peak application rate minimized in order to maximize infiltration depth. These requirements combined with the operating characteristics of center pivot irrigation systems means that sprinklers with maximum wetted diameter need to be selected in order to maximize infiltrated depth. Sprinklers with large wetted diameters also have large drops resulting in relatively high kinetic energy per unit drop volume but not necessarily the greatest specific power (King and Bjorneberg, 2012). This combined with the relatively limited range in specific power of center pivot makes sprinkler with large wetted diameters the best choice for the Portneuf silt loam soil.

Conclusions

The Portneuf silt loam soil developed a soil surface seal that reduced infiltration rate both with and without droplet impact on the bare soil surface. When the soil surface was protected during the first rainfall event, drying the soil did not increase infiltration rate for subsequent rainfall events when the soil surface was protected, but drying did increase infiltration when the soil was unprotected in the first rainfall event. For the Portneuf silt loam soil, sedimentary soil surface seals appear to be more stable than structural soil surface seals. Final infiltration rate was essentially constant between sequential simulated rainfall events when droplets impacted the bare soil surface. Final infiltration rate was inversely related to specific power of the simulated rainfall. Either with or without water droplet impact, final infiltration rate for the Portneuf silt loam soil decreased to less than 20 mm hr^{-1} within three rainfall events. Given that the Portneuf silt loam soil is extremely vulnerable to surface seal development with little difference in final infiltration rate, irrigation time must be maximized and peak application rate minimized in order to maximize infiltration depth. These requirements combined with the operating characteristics of center pivot irrigation systems means that sprinklers with maximum wetted diameter need to be selected in order to maximize infiltrated depth.

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Kinetic Energy of Water Drops Measured by a Dynamic Rain Gage System

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Abstract: *Kinetic energy is very important to predict erosive potential of any rain, natural or artificial. Few equations used are empirical and based on measurements of drop size and velocity. This presentation is focused on a set of moving rain gages to measure velocity of drops and rain intensity. The equipment was used at NSERL (National Soil Erosion Research Laboratory) at Purdue University. It was observed that values measured by this new system are easily obtained. The equipment is easy to build and can evaluate the kinetic energy of sprinklers and sprayers with no need to measure drop sizes.*

Keywords: kinetic energy, dynamic rain gage system, erosivity, DRGS

Introduction

Rain drops have been investigated in order to understand their dynamics and characteristics to estimate, mainly, soil losses caused by rain erosivity. Accordingly to Heidorn (2000), the first attempts to evaluate size of rain drops were made in 1892 by E. J. Lowe. Later, Laws (1941) used laboratory procedures and measured the velocity of rain drops and related it to diameter and height of fall. Few years later, Gunn and Kinzer (1949) used sophisticated equipment, involving pressure and electronics, to measure the velocity of drops at stagnated air, in diameter ranging from 0.07 to 5.76 mm, while the minimum size worked out by Laws was 1.2 mm. According to Niu et al (2009), data obtained by Gunn and Kinzer, although from 1949, are still used as reference at rain drop studies.

Accordingly to Eigel and Moore (1983), the most common method to determine the kinetic energy of rain, natural or artificial, requires calculation of drop physical properties, requiring knowledge of terminal velocity, drop diameter and size distribution of drops.

Several techniques were developed in the past to measure drop size and velocity. For example, Laws and Parson (1943) used the flour method to evaluate drop diameter; Eigel and Moore (1983) created the photographic method of oil immersion to evaluate drop diameter; Solomon et al. (1991) used a LASER probe to measure the diameter and velocity of artificial rain drops. Recently, Niu et al (2009) measured the velocity and diameter of convective and strati form rains at different altitudes in China. They used the LASER disdrometer technique, equipment with parallel narrow beams that, once interrupted by a drop, can identify its diameter accordingly to the number of beams intercepted. Another type of equipment had been used by Caracciolo et al (2012), referred as Joss-Valdwogel disdrometer. These authors evaluated the accuracy of kinetic energy estimated based on rain rate, as proposed by Wischmeyer and Smith (1958) and empirically calculated by equation 1, especially under high rain rate values when its value is underestimated. Bradley and Bjorneberg (2011) evaluated kinetic energy of center pivot sprayers (47.3 to 165.3 mm/h intensity) and found values to vary from 9.1 to 13.2 J/Kg.

Based on rain drop diameter, Lima et al (1993) worked out equations related to drop falling from zero initial velocity. Drop velocity at any value of time (t) can be calculated as

$$v = \sqrt{\frac{g}{C_2}} \tanh\left[t\sqrt{gC_2}\right] \tag{1}$$

where g is the gravity acceleration (9.81 m/s^2) and C2 the air drag coefficient. In an alternative form, based on the height (z), the impact velocity can be calculated as

$$v = \sqrt{\frac{g}{C_2}} \tanh\left[\cosh^{-1}(\exp[zC_2])\right] \tag{2}$$

where z is the falling height in meters. Considering a high value for z, equation 3 can be reduced to

$$v_t = \sqrt{\frac{g}{C_2}} \tag{3}$$

where v is referred as terminal velocity, known as the maximum velocity a rain drop can reach. Since natural rain drops fall from large height values, it is also considered as soil impact velocity. Several equations have been proposed to estimate C_2 based on Laws data (drop size larger than 1.2 mm).

Considering importance of erosion studies, high cost of disdrometers and inaccuracy of equations to predict drag coefficient (C_2) for small drops, this research considers that an equipment must be developed to estimate velocity and, therefore, kinetic energy of rain drops. Thus, this research investigated a dynamic rain gage system, from which kinetic energy of natural or artificial rain can be evaluated.

Theory background

A set of rain gages in which water can enter through an inclined (45 degrees) square cross section turns around a fixed circular rain gage. Based on such arrangement, although under rotational movement, the center gage (circular) is able to collect drops with vertical velocity larger than zero. The remaining gages will be filled by drops with velocity according to their position. The system is shown at figure 1.

Figure 1 – Dynamic Rain Gage System

The horizontal velocity of a rain gage positioned at a distance “r” can be calculated as:

$$Vh_r\,(m/s) = \frac{2\pi Rr}{60} \quad (4)$$

where R is the rotation speed (rpm: rotations per minute) and r is the distance from the center. Since the cross section of each square gage is inclined at 45 degrees, the vertical velocity of rain drops that can enter at a given gage is larger than 1.414 Vh_r.

Exposed to any rain, the water collected at all gages can be plotted versus the velocity of rain drops, in histogram form. The cumulative frequency can be adjusted to

$$F(V) = \frac{1}{[1+(bV)^n]^{\,m}} \quad (5)$$

where b, n and m are fitting coefficients. The first derivative of equation 6 can be easily calculated to estimate the relative frequency of rain drops falling with a given velocity.

Material and Methods

The developed system was set to turn at 123 rpm powered by a 12VDC motor under a rain simulator positioned three meters above the rain gages, at National Soil Erosion Research Laboratory (NSERL) at Purdue University. The rain simulator used works with an oscillating spray nozzle that oscillates and throws water on top of rain gages through an opening passage. Two intensity rains were used for evaluations, approximately 55 and 107 mm/h. Five rain events with duration of 7.5 minutes were evaluated for each rain intensity value. The water collected at each rain gage was used to build a histogram which data was fitted to equation 5. The rain gages had square opening section, 32 x 32mm. The central gage was circular with 32mm diameter. The water volume was measured by weighting the water collected at each rain gage and estimating the water volume considering water density equal to 1.0 g/cm^3.

Results and Discussion

Several tests were carried and the results obtained are listed at table 1.

Table 1: Velocity and Kinetic Energy of artificial rain events

Test		Velocity(m/s)			Kinetic Energy (J/Kg)		
	I(mm/h)	Right side	Left side	Mean	Right side	Left side	mean
1	56.32	3.69	3.30	3.50	6.80	5.45	6.12
2	56.84	3.46	3.67	3.56	5.99	6.72	6.35
3	56.23	3.97	3.36	3.67	7.89	5.65	6.72
4	55.35	3.46	3.84	3.65	5.98	7.37	6.66
5	53.57	3.74	3.65	3.70	7.01	6.66	6.83
Mean	55.66	3.66	3.56	3.62	6.73	6.37	6.54
CV	2.31	5.84	6.37	2.30	11.83	11.59	4.48
6	106.73	4.11	3.51	3.87	8.46	6.17	7.48
7	108.23	4.05	3.80	3.94	8.22	7.23	7.77
8	105.14	4.06	3.75	3.93	8.24	7.03	7.74
9	111.21	3.88	3.57	3.75	7.52	6.36	7.02
10	107.03	3.98	3.72	3.88	7.93	6.92	7.52
Mean	107.67	4.02	3.67	3.87	8.07	6.74	7.51
CV	2.10	2.22	3.38	1.95	4.49	6.74	4.01

CV: coefficient of variation (%)

Kinetic energy of rain was calculated as well as velocity considering rain gages at both sides of the central gage. Values listed on table 1 allows to conclude that despite the fact that intensity has approximately doubled, the velocity slightly increased from 3.62 to 3.87 m/s while the kinetic energy increased from 6.54 to 7.51 J/kg. In fact, this was expected (velocity would remain similar) since the rain intensity is increased simply by increasing the number of oscillations per minute at the rain simulator, i.e., the rain is the same, only the number of pulses (oscillations) has changed.

A histogram of rain drops can be built as plotted at figure 2. Observed and fitted values of cumulative frequency are plotted as well as the relative frequency – f(V). As can be observed, good fittings were obtained and all drops fell with velocity under 10 m/s.

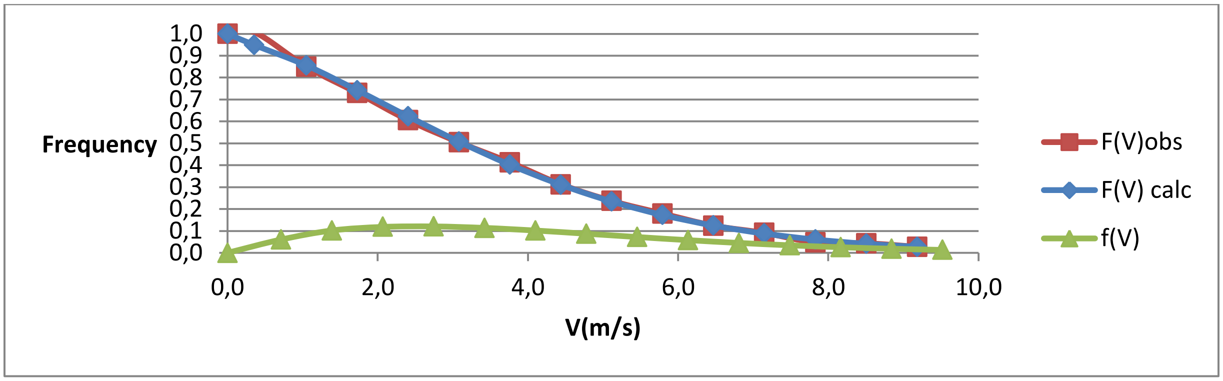

Figure 2: Histogram of cumulative (F) and relative (f) frequencies of rain drops

Comparatively to data found by Bradley and Bjorneberg (2011), the rain generated by the rain simulator tested has lower kinetic energy than that of center pivot nozzles (Nelson D3000, S3000 or R3000) with approximate flow rates of 2.5 m3/h, when KE varied from 9.1 to 13.2 J/Kg.

Conclusions

The dynamic rain gage system allowed the measurement of kinetic energy with no need to measure the drop size. It is simple to build and avoid empirical estimates of kinetic energy subject to errors.

Acknowledgments

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The Future of Water for Agriculture: Pressures in the Colorado River Basin Perceived by Ag Producers [1]

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ABSTRACT

Water used for agriculture in the Colorado River Basin and throughout the western United States is being eyed by those seeking water for other uses: urban, environmental, recreation, energy production. As "buy and dry"—buying ag water and permanently removing it from the land—is increasingly losing favor because of its negative repercussions, some are experimenting with alternatives. These alternatives include rotational fallowing and deficit irrigation to free up some of a farmer's ag water for temporary, often drought-year, leases. Other options including water banking and multiple benefit infrastructure projects. We and others have used the term "water sharing" to describe strategies being considered.

While policy makers, scientists, and academicians are busy researching and exploring these opportunities, few agricultural producers have been actively involved. At a meeting at the Colorado River Water Users' Association convention in Las Vegas, Nevada, in 2011, one manager of an irrigation district said, "We don't like this term 'water sharing.' We own the rights to our water; if you want a share in it, bring money to the table." Terminology aside, some ag producers are showing interest in these alternatives that could boost their profit line and allow them to keep farming.

Believing it is important to understand the range of attitudes held by agricultural producers in regard to the future of their water, researchers from the seven land grant universities in the Colorado River Basin are interviewing and surveying farmers and ranchers and those who manage their water. The results of our findings may lead to pilot projects cooperatively led by ag producers and universities to assure that ag interests are at the forefront of any "water sharing" or temporary transfer strategies. Here, we share preliminary findings.

Introduction

Colorado State University's Colorado Water Institute is spearheading a USDA-funded research project on water for agriculture in the Colorado River Basin (CRB). Carried out in partnership with the seven CRB land grant universities (Colorado State University, University of Arizona, University of California, University of Nevada, New Mexico State University, Utah State University, and University of Wyoming), we want to find out what

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[1] A version of this paper is forthcoming in Colorado Water, Newsletter of the Water Center of Colorado State University.

farmers, ranchers, and water managers are thinking about the current and future status of their agricultural water. Through this project, we hope to identify ways in which land grant universities can better assist agricultural water users and managers with the challenges they are facing.

Here, we briefly report on our progress with the research, which includes in-depth exploratory interviews and survey and mapping activities.

The Interviews

We have completed in-depth telephone interviews with more than sixty farmers, ranchers and water managers in all seven CRB states. Our other university partners helped us identify areas of high significance for agricultural water within each state and assisted us in contacting potential interviewees. We asked interviewees open ended questions about what they felt were the main pressures, if any, on agricultural water, how farmers were responding, how they saw the future of agricultural water and how land grant universities might help. Although we are in the process of analyzing the rich information from these discussions, below we provide some preliminary thoughts on what we have learned.

The Survey

The project team will be administering an online survey of farmers and ranchers in selected counties of Colorado and Arizona who use Colorado River water. The survey will address similar topics as those covered in the interviews, but will gather information from a broader audience in order to help formulate collective solutions to keep irrigated agriculture viable in the Colorado River Basin. The survey seeks to:

- Identify what CRB agricultural water users think about the current and future state of their water supplies and production activities.

- Identify and compare the attitudes, beliefs, and perceptions held by agricultural water users towards the changes and pressures they are/are not facing with their water supplies, changes in water law and policy, and how to meet future water demands.

- Gather data on agricultural producers' interest and involvement in temporary and permanent agriculture water transfers and water banks.

- Identify how agricultural producers work cooperatively with other agricultural and non-agricultural stakeholders.

- Identify how land grant universities can better assist farmers and ranchers with the challenges they are facing, or will be facing with regard to their agricultural water.

- Gather ideas for projects, partnerships, and other initiatives to work with agricultural producers to help address the challenges they are facing with regard to their water and operations.

The GIS Mapping Activities

The project team conducted a mapping exercise in December 2011 with approximately 40 agricultural representatives from the CRB. A geospatial database is being created to help us better understand how agricultural water is administrated and managed in the seven CRB states. Data collected includes:

- political jurisdictions including counties, states, tribal lands, counties, and municipalities
- hydrologic boundaries defined both by state and by hydrologic unit
- agricultural water jurisdictions within the basin including Bureau of Reclamation projects, irrigation districts, water conservancy districts and conservation districts, water users associations, and private irrigation and ditch companies
- environmentally sensitive areas such as salinity control areas, designated wild and scenic stretches of the Colorado River and tributaries, and areas where endangered species are identified as of concern or are actively being protected.

Maps have also been an integral part of the interview process. With help from water leaders in each state, we created maps to help us locate areas where agricultural water is especially important and where we needed to interview individuals and key water organizations' representatives. Though the interviewees' identities are confidential, during the interviews we referenced digital maps showing local political jurisdictions, waterways and other features to help us locate our discussion in the complex geographic space occupied by the interviewees.

All of the base maps were created from a comprehensive geospatial database of the CRB that is being developed under the direction of CSU professor, Dr. Melinda Laituri.

Preliminary Results from the Interviews

Agricultural water users across the CRB are of course, very diverse. They operate across geographical contexts that vary from Upper to Lower Basin, high-altitude to sea level areas, and from forested to semiarid regions. They engage in a wide range of agricultural activities, from cattle ranching and cropping of pasture, alfalfa and small grains, to high value vegetables, fruits, nuts and more. Agricultural water users and managers operate under the 1922 Colorado River Compact and the Law of the River, yet each state provides distinctive frameworks for agricultural water use, management and transfer.

Agricultural water users and managers operate in a complex set of organizational contexts, from individual surface water diverters and groundwater users to ditch companies, irrigation districts, and water conservancy districts. Nevertheless, agricultural water users and managers report a number of common challenges (though their experience of them is shaped by geographic location, the history and seniority of their water rights, the type of agriculture and ranching, the proximity of urban areas and other competing water users, etc.).

These common challenges include uncertain water supplies, extended drought and the threat of climate change, and competition and conflicts with other water users within agriculture and from energy, environmental, recreational, and municipal/industrial sectors.

Many respondents have talked about the need for storage to manage effectively for multiple use and conservation but often express concern about the barriers posed by negative public views of storage and time-consuming and expensive permitting processes. Conjunctive management of surface and groundwater poses increasingly complex problems of water access and management.

Many have commented on how government regulatory frameworks, especially the Endangered Species Act, the National Environmental Protection Act, the Clean Water Act and health and safety regulations, have fundamentally changed not only how water is used, but agricultural production itself.

Many farmers have expressed concern about the need to strengthen public understanding of the importance of agriculture for a secure and healthy food supply. Many also have observed that the key role irrigated agriculture plays in creating ecological and amenity values is not well understood by many in the environmental and recreation communities. Others have remarked on the increasingly litigious environments in which discussions of water are occurring and suggested that more real progress can be made when people can stay out of court.

Our interviewees have also spoken, often with great poignancy, about uncertain futures for family farms and agribusinesses as younger generations choose not to continue in agriculture. Numerous interviewees have spoken of farming's future as one integrated with growing cities, with fewer traditional operations and many smaller "amenity" farms.

Some farmers spoke of selling parts of their land and water rights to developers or even acting themselves as development investors, with returns reinvested in agriculture elsewhere or in helping secure their retirement.

It seems clear that agricultural water users are not affected the same way by the challenges facing them today. Many interviewees describe themselves as positioned to move ahead and either surmount these challenges or adapt to them in new and productive ways. These well-positioned users of agricultural water are found in all parts of the CRB represented by our interviews. Yet agriculture and agricultural water is described as strongest where geographic and climatic conditions allow highly productive agriculture with year-round, high-value commercial cropping.

Water users with the most senior water rights are more cushioned from the uncertainties of an intensively used river and of supplies threatened by extended drought and predicted climate change. Though having urban areas nearby generally results in significant pressures from non-agricultural water demands, transportation and communication infrastructure also mean lower costs of production and marketing. Significantly, it is in these areas that interviewees spoke more consistently of new generations entering farming, ranching and related agribusiness.

Agricultural water users working in geographical areas where climatic and soil conditions pose higher obstacles to productivity, shorter growing seasons, and greater isolation from markets, face special challenges in adapting to new water pressures. More of these respondents spoke poignantly about their sense of the threats to a traditional farming way of life, as their children seek futures outside of agriculture.

Yet these interviewees are clearly not giving up; on the contrary, they express deep commitments to what is in many cases, multi-generational investments in their land, water and agricultural way of life. They also express a strong commitment to providing food for our society, and their concern for national food security. Moreover, they are working hard to develop innovative ways to protect their water and their communities.

Indeed, interviewees throughout the CRB have talked about innovative strategies they are developing to overcome or adapt to pressures on agricultural water. In many areas, as in California, Arizona and Colorado, agricultural water users and managers have embarked on new agreements with large urban water users to develop water supplies for multiple objectives, including urban, environmental, recreation and agriculture. Several water managers have described their organizations' services to multiple user groups and their need to plan for more urban and municipal demands while maintaining support for agriculture.

In several areas, such as Wyoming. Colorado and New Mexico, multi-stakeholder forums and organizations have formed to try to manage conflicting claims and perspectives on water by bringing agriculture, environmental, recreation, and other groups to the negotiating table. These initiatives are not easy and have had mixed results, but participants in successful experiences have spoken of what can be achieved with key visionary leaders, a focus on common interests of all parties in healthy local economies and riparian ecologies, willingness of all user groups to compromise, and a commitment to generating concrete results quickly, even if on a small scale.

Other innovative responses reported by interviewees include diverse groundwater recharge programs, formal and informal water banking and a range of leasing mechanisms. Numerous interviewees have reported on innovative approaches to planning storage as a key to developing secure future supplies of water for multiple uses, including agriculture, environmental, and recreational uses.

What Needs to be Done?

Our interviewees have spoken of possible paths to a positive future for agricultural water. They suggest that the broader public might be helped to better understand the importance of irrigated agriculture, not just for securing high quality and safe food for our nation, but also for creating significant environmental and amenity values. As one Wyoming rancher put it, "This is an oasis in the high desert. But God didn't make the oasis. It's man-made. It takes lots of water, diverted regularly in almost impossible quantities to keep it that way."

Interviewees remarked that regulatory frameworks could better recognize both the continuing need for a viable agriculture throughout the Basin as well as its obstacles. Competing water users/stakeholders could develop more effective ways to negotiate, based on understanding if not agreement with other perspectives, and the need for a strong agriculture in the future.

What is the Role of Land Grant Universities?

Most interviewees have expressed positive views of land grant universities. They speak of the Extension agents who help them improve efficiency of irrigation technology and water management, introducing new seeds, and implement better soil practices. Interestingly, although most of our open-ended questions about the agricultural water community's challenges stimulated discussion of issues that are largely political, economic, social and cultural in nature, relatively few respondents had experience with universities helping with these issues.

This suggests to us that land grant universities have an opportunity to bring to bear new kinds of social science research and outreach on the problems facing agricultural water users and managers, in addition their traditional strengths in natural science and more technical disciplines.

Posting of Results

Results from the Addressing Water for Agriculture in the Colorado River Basin project will be summarized and posted on the project website in the spring of 2013. (www.CRBagwater.colostate.edu)

A Demonstration of Energy & Water Savings Potential from Optimal Irrigation Management and Precision Application

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Abstract. *Optimal irrigation management is being demonstrated on three farms in Oregon, Washington, and Idaho, during 2012 as part of a multi-year effort to develop and demonstrate the effectiveness and profitability of an integrated solution. Integration includes high resolution soil mapping, variable rate irrigation, on-site ET, capacitance and neutron probe soil moisture measurements, optimal irrigation methodologies, flow meters, energy use monitoring via smart meters and yield mapping of results. The objective of the demonstrations is to show increased profitability based on optimizing inputs. Initially the information from each of these sources is integrated into a management system, Irrigation Management Online, specifically designed to schedule irrigations when water supplies are limited. The management system provides optimized scheduling based on multiple information sources and includes the grower as a critical component of the decision process. This paper will present the preliminary results from the 2012 season and describe plans for following years.*

Keywords. Irrigation Optimization, Variable Rate Irrigation.

Introduction

The demand for fresh water is projected to exceed renewable supplies by 2025 (Postel et al., 1996). The world demand for food is increasing because of increased population size and increased demand for resource intensive products (beef, poultry, etc). For irrigated agriculture, at the intersection of these two resource limitations, water shortages will become not only common but even standard operating conditions. This leads to the obvious conclusion that changes must occur, and agriculture, the largest consumer of fresh water, is expected to make big changes in water use. Part of the solution is expected to come from improvements in crop characteristics to reduce water needs and increase stress tolerance (Baulcombe, 2010). However, it is generally recognized that the developing water shortages will also force fundamental changes in the way irrigation is managed (English et al., 2002). Irrigation management will necessarily move from simple stress avoidance (a biological objective) to optimization based on net returns to water (an economic objective). Much more sophisticated irrigation management tools will be needed to support optimal decision making in a water-limited future. These tools will be driven by technologies for environmental monitoring, operational monitoring, and precision irrigation. The complexity of such optimal irrigation advisory tools will require a development foundation that facilitates integration of technologies and information from a variety of sources. However, adoption of these technologies will, as with any new technology, be limited by its economic viability. The object of the project described here is to demonstrate the economic potential of optimal irrigation in general and variable rate irrigation in particular.

The demonstration project will achieve the following:

1. Demonstrate savings in water and energy associated with optimal, variable rate irrigation.
2. Determine the cost effectiveness of current irrigation technologies by balancing the capital investment against financial gains from energy and water savings.
3. Determine the relative value of each data source (instrument), both in terms of decision making power and dollars.
4. Provide the foundation for development of data exchange standards and an Application Programming Interface for irrigation management.

Optimal Irrigation

Economically optimum irrigation management is fundamentally different, and more difficult, than conventional irrigation. Economically optimal irrigation implies some level of deficit irrigation (English et al., 1990), (English and Raja, 1996),(English and Nuss, 1982). While the conventional paradigm is to irrigate as needed to avoid crop stress, deficit irrigation involves controlling crop stress in spatially variable fields. The conventional method is essentially a balancing of irrigation and evapotranspiration. Optimal irrigation scheduling is a decision process. The information needed to implement optimal scheduling is orders of magnitude more complex than conventional scheduling. The irrigation manager must account for soil heterogeneity, the spatial variability of applied water and crop responses to water stress. This complexity is increased by the fact that fields are not managed in isolation; the entire farm is considered when allocating water supplies. Accounting for these factors will require: (i) explicitly characterizing field heterogeneity, the uniformity of applied water; (ii) modeling the disposition of applied water; (iii) estimating crop yields under variable water stress conditions; and (iv) quantifying the marginal costs of crop production (largely energy costs in the case of the farms that will be the focus of this project). For this reason, sophisticated modeling and management tools are needed to implement optimal scheduling.

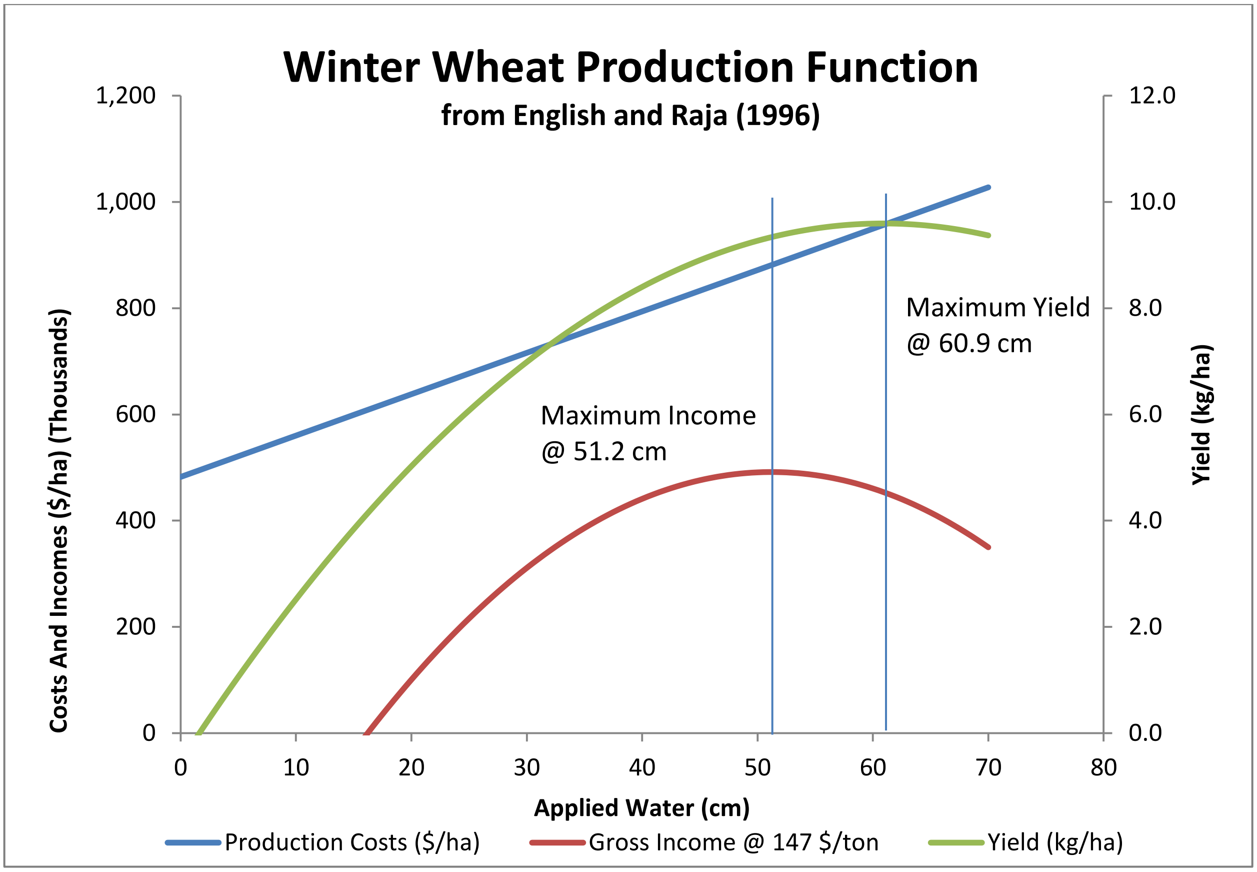

Figure 1 A production function developed for Winter Wheat at Hermiston, OR. The maximum income occurs when the water application is 16% less that that required for maximum yield. This reduction in water application results in a reduction of crop water use which is the deficit in Deficit Irrigation.

Irrigation affects and is affected by nearly all farm operations. Limitations on resource availability increase the complexity of the effects on irrigation management. To include these constraints in an optimization algorithm involves codifying the constraints in a manner appropriate for an optimization framework. Encoding all possible constraints is not an achievable goal because we cannot possibly know all the constraints *a priori*. Including most of the constraints would still involve constructing quantitative representations of the different farm processes. Instead of building a simulation of the whole (or nearly whole) farm enterprise, IMO takes a different approach. The central thesis of IMO is that the best way to implement or express these constraints is to build a system that includes the only entity that is aware of all these constraints: the grower.

This system, known as Irrigation Management Online (IMO), explicitly analyzes irrigation efficiency and yield reductions for deficit irrigation, performs simultaneous, conjunctive scheduling for all fields in the farm that share a limited water supply, and employs both ET and soil moisture measurements in a Bayesian decision analysis to enhance the accuracy of the irrigation schedules. IMO is described in detail in (Hillyer, 2011), and (Hillyer et al., 2009); the complete details of its implementation are beyond the scope of this paper.

An Integrated Approach

A wide variety of technogies and methods have been developed for irrigation management. The technologies for Center Pivot control have been reviewed by Kranz et al. (2012) and the potential for adaptive control was analyzed by McCarthy et al. (2011). Many of these technologies still operate in isolation. Integrating the information to produce an irrigation schedule requires a significant time investment for the irrigation manager. This systems integration task is part of the focus of the demonstration and the overall project. The goal is to produce a system that demonstrates the potential time and effort savings obtainable from automating the data integration task. Furthermore, the data being integrated will be used to drive the IMO system to produce additional value in the form of more precision for irrigation management. Figure 2 shows a conceptual overview of the data sources that will be integrated.

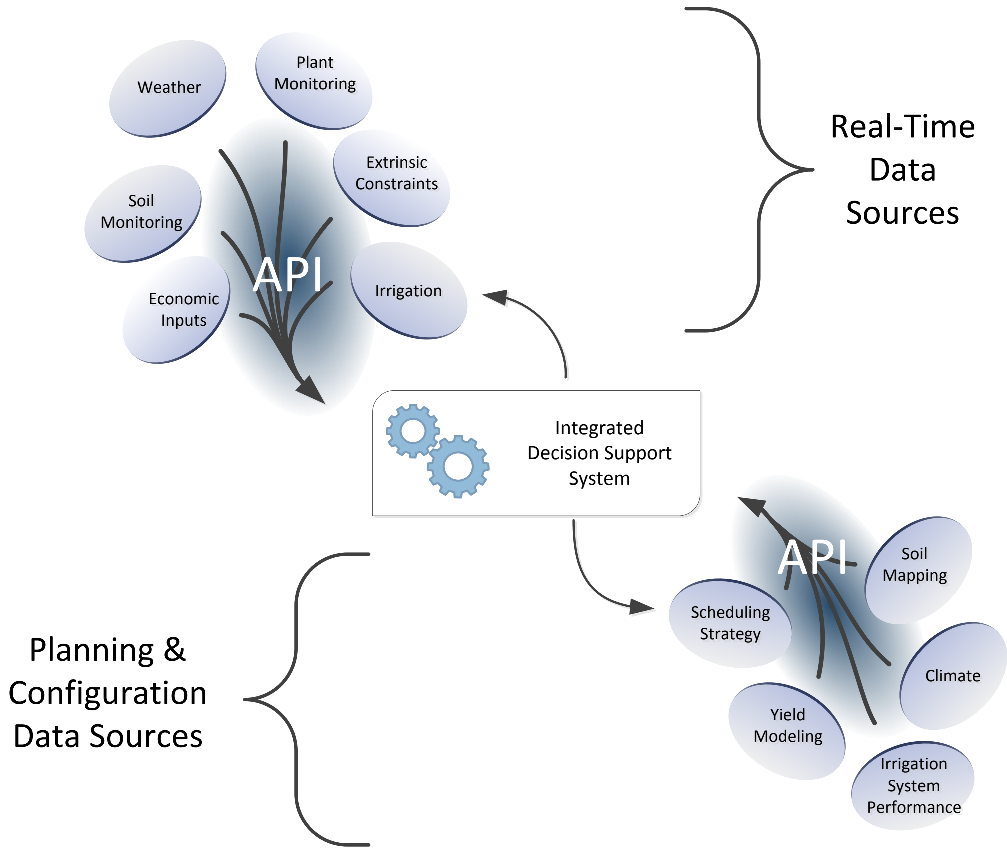

Figure 2 Conceptual overview of the integrated system

Data acquisition is only one part of the scheduling process shown in Figure 2. Making data easy to obtain and presenting it in clear ways is a valuable feature but the real power of irrigation schedulers lies in the potential for using the information to drive calculations. In this sense, an irrigation scheduler is also a decision support system. Mohan and Arumugam (1997) indicated that Expert Systems are viable and effective tools for irrigation management and stressed the need to include other aspects of irrigation management such as canal and reservoir operation. This need was also indicated by Clyma (1996) who concluded that scheduling services are not adequately integrated with other farm operations that hold greater importance than irrigation decisions. The need for combining irrigation tools with crop growth models has been emphasized in the past (Wolfe, 1990) and continues to be emphasized more recently (Woodward et al., 2008). The cost of Developing the yield response functions that are needed for optimal management is a limiting factor, however Variable Rate Technology does make this more feasible (Bullock et al., 2009).

One of the goals for this demonstration is for the benefits of system integration be transferrable beyond the scope of this demonstration project. To that end, development of data exchange standards and an Application Programming Interface for irrigation management is being developed in parallel with the demonstration projects. The details of the API are beyond the scope of this paper. Once the demonstrations are complete, an open source version of the IMO system, including the systems integration features, will be made available. The open source release will serve as an example for other interested developers. Serve as a "guinea pig" for (rather than a competitor to) informing future development of irrigation management systems.

Variable Rate Irrigation

Site-Specific Variable Rate Irrigation (VRI) is a system where a center pivot irrigation system is equipped with the capacity to actuate valves for groups of sprinklers, or to regulate its speed during operation. A control system is used to open and close the valves at various rates (or change the speed) based on the position of the pivot and a desired application depth. VRI systems have been described in detail by (Evans et al., 2012), (Evans and King, 2010), and (Sadler et al., 2005). One aspect of VRI that has not been studied is the potential for mitigating some of the undesirable effects of deficit irrigation. When deficits are imposed on a field they are generally estimated based on an average for the whole field. Because no field is completely uniform, some areas of the field will experience more stress than the targeted amount. This can produce visibly bad areas of yield response even though the overall yield response is still optimal. By using the VRI system, it may be possible to produce increased uniformity of yield response and improve the qualitative effect of visibly bad areas in a field.

To test this theory the IMO system will manage two fields (with the same crop) at the same. One of the fields will be managed with a VRI system and the other with a uniform system. After harvest the shape of the statistical distribution of yield (rather than the overall magnitude) will be compared between the two fields. This comparison will be replicated at each of the demonstration sites. If the shape of the distribution produced by the VRI system is significantly less correlated to the limiting soil physical properties, it may be possible to show that the VRI system has produced more uniform yields relative to a non-VRI system. This yield normalizing feature could enhance the economic viability of VRI and improve the qualitative performance in the form of better looking fields.

Demonstration Project

The demonstration project was started in the spring of 2012 and is planned to be a multi-year effort. Three farms in the Colombia Basin agreed to participate in the demonstration. These farms were selected on the following bases: 1) high lift requirements for pumping (so that energy costs would be significant), 2) farm/irrigation managers that were willing to experiment with new technologies, 3) the manager must be willing to act on the irrigation recommendation provided by the integrated system, 4) greater than 500 acres in production. Each farm received the full complement of instrumentation, monitoring, and analysis described below effectively producing three replications of the demonstration. A summary of the fields used during the 2012 season is shown in Table 1.

Table 1 Summary of Demonstration Sites

Field Number	Integration Level	Crop (2012)	Size (Ac.)	Pumping Lift (ft.)	Location
18	Level 3	Winter Wheat	69	≈750	OR
11	Level 2	Winter Wheat	82		
17	Level 1	Alfalfa (mature)	125.3		
25		Potatoes	119.2		
102	Level 3	Alfalfa	125	≈750	WA
107	Level 2	Alfalfa	72		
109	Level 1	Alfalfa	125		
210		Alfalfa	125		
2	Level 3	Winter Wheat	136	≈125	ID
1	Level 2	Winter Wheat	155		
3	Level 1	Sugar beet	147		
6		Sugar beet	134		

The following components were installed or conduced at each farm:

- **Variable Rate Irrigation:** At each site, one pivot was retrofitted with a Valley Variable Rate Irrigation System (Valmont Industries, Inc.) and the panels were upgraded where necessary. The system was installed with 30 sprinkler banks. Valmont engineers supervising the installation selected the bank locations. Two of the farms are using re-use water (one from a potato processing plant, the other from animal waste). Because of concerns about potential valve clogging, these two sites were equipped with pneumatic valves rather than the typical hydraulically actuated valves.
- **Soil Mapping:** High-resolution soil maps were produced by a soil mapping service (Soil and Topography Information, Inc.) using a combination of electromagnetic sensing and physical soil sampling. The soils data was used to produce data layers for several soil properties including holding capacity, field capacity, and root zone restriction depth.
- **Flow Monitor:** ultrasonic flow meters (GE Panametrics) were installed on the pivots equipped with VRI. Water use records for the other fields will be derived from records kept the the software used to actuate the pivots.
- **Weather Monitoring:** Each farm was equipped with a primary weather station (Automata, Inc). equipped with the sensors required to calculate reference ET. Additionally, each field had secondary a weather station placed well within the field boundary. This secondary weather station was equipped with temperature and relative humidity sensors and radio communication ET calculations were performed using the ASCE Standard equation (Allen, 2005).
- **Soil Moisture Monitoring**: each field was equipped with two neutron probe tubes and readings were taken on a weekly basis. In the fields where soil mapping occurred, the tubes were sited such that the tubes were approximately in the upper and lower quartiles of the Plant Available Water. In two fields at each farm, two types of capacitance probes were also installed (AquaCheck and Decagon 10HS). These probes were connected to the weather stations to take advantage of their telemetry capacity.
- **Localized Yield Modeling**: At each site, a local calibration of the FAO33 yield reduction model was produced using historical yield records. This calibration will enable generation of more precise yield maps and enable consideration of the value of these maps relative to default or regionally estimated yield calibrations.
- **Yield Mapping**: harvest monitors with gps tracking will be collected at the end of each season wherever possible (technical issues limited the collection of yield maps during the 2012 season). These data will be used to compare the spatial variability that was expected from the yield model.

In the alfalfa fields, infrared photographs were used and alfalfa yield distributions were estimated using the methods described by (Mitchell et al., 1990; Pinter et al., 2003; Hancock and Dougherty, 2007).

To facilitate comparison of various combinations of technologies, the fields are grouped in to three different levels of integration. Each level represents a significant improvement in scheduling precision and potential for water & energy savings relative to the previous level. *Level 1* is the equivalent to basic Scientific Irrigation Scheduling (SIS) where a water balance is used to drive irrigation scheduling. However, this capacity is enhanced by utilizing in-field temperature and relative humidity sensing to refine ET estimation, and neutron probe measurements to correct the water balance. *Level 2* builds on Level 1 by adding additional soil moisture monitoring and high resolution soil maps. The soil maps enable explicit consideration of spatial variability which will lead to more accurate yield estimates and more robust management capacity. The additional soil moisture monitoring enables increased temporal resolution and the opportunity to assess data integration issues with different sensors, data loggers, and telemetry. *Level 3*, the final level, adds VRI capacity.

Preliminary Results

All of the previously mentioned instrumentation was installed during the spring of 2012. A series of logistical issues and technical problems prevented the full implementation that was originally planned. While these issues prevented implementation of the irrigation scheduling there was relevant progress towards the goal of a robust demonstration.

- The logistical and technical issues have highlighted several “bottlenecks” to data integration and have informed the development on the API.
- A majority of the environmental monitoring instrumentation was installed and operational for a significant portion of the irrigation season. These data enabled a robust calibration of the IMO system. A soil moisture graph, produced by IMO, is shown in Figure 3. The black squares are neutron probe measurements taken during the latter half of the irrigation season.
- The localized yield models were constructed for winter wheat and alfalfa.

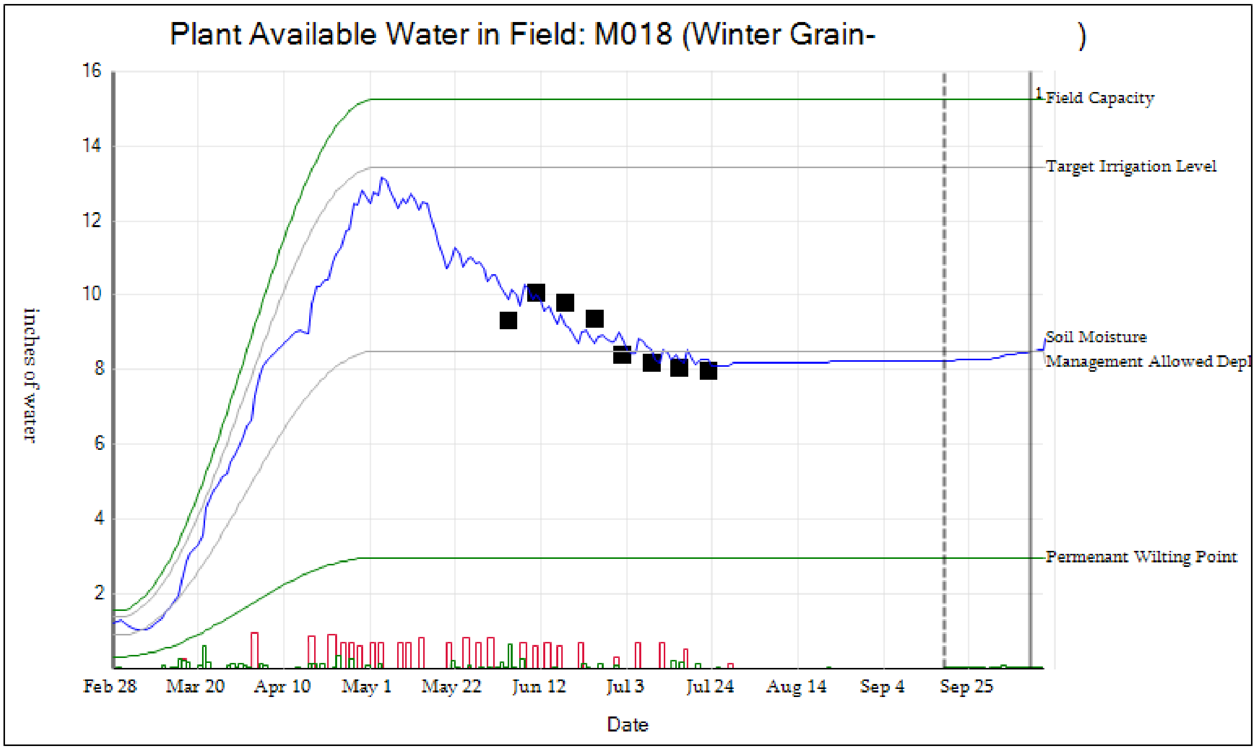

Figure 3 Trace of Estimated Soil Moisture produced by integrating soil moisture measurements, weather data, and water use records.

Conclusion

A demonstration of the economic potential of optimal irrigation and variable rate irrigation was conducted on three farms in the Colombia Basin during the 2012 irrigation season. This demonstration employed substantial environmental monitoring, and was integrated (to the best degree possible) into a decision support system that generated irrigation recommendations. This demonstration is a multi-year effort and the subsequent years are anticipated to utilize a fully integrated management solution. It is also anticipated that there will be additional cooperating farms during the 2013 irrigation system.

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Water Productivity of Cotton in the Humid Southeast – Experimentation

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Abstract: *Global challenge for the coming decades will be increasing food and fiber production with less water. This can be partially achieved by increasing crop water productivity (WP) - yield or biomass produced per unit water used. While there is abundant information on cotton water use and yield relationship in arid regions, relevant information in humid regions is not as well developed. The objective of this study was to quantify cotton water use and in-season growth parameters in the humid Southeast U.S.A., where water conservation is an emerging issue. Irrigation experiments were conducted in 2009 to 2011 under field conditions as well as under an automatic rainout shelter at a Clemson University research site near Blackville, SC. Season-long data were collected under irrigation regimes ranging from dryland (i.e., no irrigation) to fully irrigated. Cotton seasonal water use ranged from 320 mm at 33% irrigation to 718 mm at full irrigation. Water productivity in the three years ranged from 0.52 to 0.71 kg of seed cotton per* m^3 *of water applied (irrigation and rainfall). Water productivity normalized for local climate was nearly the same during the three years, averaging 12.5* g/m^2*. Cotton WP and water use values quantified in this study are useful for modeling yield response to water stress and evaluate effects of alternate irrigation regimes and intermittent drought on cotton productivity.*

Keywords: Water productivity, Water use efficiency, Cotton, Evapotranspiration, Irrigation

Introduction

Cotton (*Gossypium hirsutum L*) is cultivated in many countries under both rainfed and irrigated conditions. In the U.S.A., cotton is grown in 17 states across a vast region known as the Cotton Belt. Use of irrigation has been increasing across the humid areas of the Cotton Belt for the last 20 years. In the Cotton Belt as with many parts of the world, irrigated cotton is a considerable water user, but for good reasons. Irrigation can boost yield as well as stabilize yield and quality by ensuring adequate soil water during the entire growing season or at least during critical growth stages in areas where water resources are limited.

A useful relationship between yield and water use is crop water use efficiency or water productivity (WP). A more biological definition of WP is given as biomass or yield produced per unit of transpiration (Steduto et. al., 2007). There is limited control on the part of the irrigator to alter this efficiency. However, WP defined as “the aboveground dry matter or yield (kg) produced per unit land area (m^2) per unit of water applied (m)” is more informative as it is largely influenced by the performance of the irrigation system and the degree of water losses beyond crop transpiration. Regardless of the units used, quantification of WP under field conditions is challenging as estimates of crop transpiration and/or evapotranspiration (ET) are needed. This is even more challenging in regions with frequent rainfall, such as in the Southeast due to difficult-to-determine contribution of rainfall to soil water storage.

For the Cotton-Belt, cotton ET increases by about two-fold from the humid East to the arid West. For example, cotton in the desert Southwest requires as high as 1000 mm of water per season for long season varieties while mostly between 500 and 650 mm in the humid Southeast. In Southeast Coastal plains, Bellamy (2009) measured seasonal cotton ET values of about 570 mm using a 1 m^2 lysimeter. In Georgia, Suleiman et al. (2007) used FAO-56 crop coefficient procedure to estimate ET values of 370, 584, and 640 mm for 40%, 60%, and 90% irrigation treatments, respectively. Modern, water efficient cotton varieties tend to provide at least 27 kg (60 pounds) of lint and 41 kg (90 pounds) of seed for every 25 mm (1 inch) of water used. Data from a wide number of locations shows cotton WP values ranging from 0.41-0.95 kg/m^3 for seed cotton yield (Zwart and Bastiaanssen, 2004). Bellamy (2009) and Khalilian et al. (2012) reported WP of cotton from 0.42 to 0.66 kg/m^3 for different cotton varieties grown in SC. While there is a large collection of information for yield and water use related to cotton in arid regions, relevant information under humid conditions is not as well developed.

The main objective of this study was to determine water use, WP, and in-season plant growth parameters of cotton in the humid Southeast. The experiments were conducted in 2009 and 2010 under field environments and in 2011under a controlled environment utilizing an automated rainout shelter at a research facility near Blackville, SC. The data was subsequently utilized in a companion study to model cotton yield response to water using the recently released AquaCrop model by the Food and Agriculture Organization (FAO) of the United Nations. Results from the second study are presented in Qiao (2012) and Qiao et al. (2012, in this proceedings).

Methods and Materials

Field experiments were conducted at the Edisto Research and Education Center (EREC) of Clemson University near Blackville, South Carolina (see Qiao, 2012 for detail). Replicated tests were conducted in three season-long experiments during 2009 to 2011 growing seasons to determine water use, WP, and growth parameters of cotton under different irrigation regimes ranging from no irrigation (dryland) to meeting 100% of full cotton water requirements. Experiments in 2009 and 2010 were conducted on a typical coastal plain soil (Barnwell loamy sand), in a field named "E5". Experiments in 2011 were conducted in field plots with Wagram sand under an automated rainout shelter that covered the plots during rainfall events.

Deltapine Land (DP 0935 B2RF) cotton variety was planted on May 22, 2009 and on June 7, 2010 at 96 cm row spacing. Fertilizers, herbicide and insecticide were applied as needed. In 2009, the experimental site was divided into twelve 7.9 m long plots. Field was disked and subsoiled to a depth of 30cm before planting. Four treatments of 0, 33, 66, and 100% irrigation were planned in 2009, but excessive rainfall during the season made it impossible to maintain irrigation treatments, with all treatments then regarded as well-watered. In 2010, the experimental site was divided into 9 plots. Each plot was 20 m long, 36 rows wide. A 3 m alley between each plot was used to separate test plots. The nine plots were grouped into 3 blocks with irrigation treatments of 0%, 75%, and 100% randomly assigned to each plot.

Data collected from the rainout shelter experiment in 2011 was used to parameterize the AquaCrop model mainly because the shelter data was of higher detail than the field E5 data and the rainfall complications were eliminated by the shelter. The area under the rainout shelter (Figure 1, left) was divided into nine (4-rows by 5m) plots and the three irrigation treatments (33, 66, and 100% of the full irrigation) were replicated three times. The cotton variety DP 0924 B2RF was planted on 16 May using a four-row JD planter and carried to yield using recommended practices for seeding and nutrient application and insect and weed control. Cotton was hand harvested on Oct 6, 2011.

The shelter was moved by two independent, twin-drive mechanisms, one on each side of the building. The shelter could move at 15 m/min on a metal railway built on concrete, and could cover the whole plot in approximately one min.

Figure 1. View of the rainout shelter plots (left) and the linear move system with LEPA (right)

This rainout shelter was automated by using a rain-clik sensor (Hunters Rain-clik sensor, Hunters Inc.), which triggered a relay to start the motors and move the shelter to cover the plots from rainfall. When the rainfall stopped, the rain-clik disks shrank by drying and released the micro switch, causing the motors to run in reverse returning the plots to uncovered conditions. The drying process took about 30 minutes under normal conditions.

In all experiments, volumetric soil water content (SWC) was measured at 15 cm intervals by a 503DR Hydroprobe neutron probe. Readings were taken in the mid-morning and before irrigation. For field E5, readings were taken at weekly interval to the depth of 90 cm. For the rainout shelter, readings were taken to the depth of 60 cm. The neutron probe readings were taken once a week in all plots and twice a week in the 100% irrigation treatment plots.

In all fields, irrigation was initiated as soon as possible after soil water content in the root zone approached 50% of available soil water. A linear move irrigation system with LEPA nozzles was used for irrigation of plots in field E5 (Figure 1, right). At the rainout shelter, cotton was irrigated using drip tapes with 30 cm spacing emitters (1.16 L/hr flow rate). Drip laterals were placed on the soil surface next to the row. For the 100% treatment, irrigation was initiated after 50% of available water was depleted. Irrigation was then applied to bring the soil water contents to field capacity. In other treatments at the shelter, irrigation occurred at the same time but the duration was reduced to 33% and 66% of the full irrigation.

Cotton growth development was monitored in terms of growth stages, canopy cover, and aboveground dry biomass. Canopy development was monitored by AccuPAR LP–80 (Decagon Devices, Inc.) as well as a digital camera at the same time on weekly intervals. AccuPAR LP–80 measures Photosynthetically Active Radiation (PAR) in the 400-700 nm wavebands. When readings were taken, the photosynthetic bar was located at the center of the plant row (Figure 2). Readings were taken both above and below the plant canopy near solar noon in each plot and canopy cover was calculated as one minus the ratio of the PAR readings.

Figure 2. Measurement of PAR_{above} (left) and PAR_{below} (right) at the shelter plots

Digital photos were also taken vertically downward at the center of plant row in each plot. A 96-cm stick was placed in the middle. Photos were then cropped exactly to 96-cm width. VegMeasure version 1.6 (VegMeasure Project, Oregon State University) was used to analyze the pictures for green cover.

During the growing seasons, two plants were sampled each week from each plot for biomass determination. Plant samples were dried at 65℃ for 48 hours to get dry weight of biomass (g). Aboveground dry biomass was multiplied by plant population to obtain aboveground dry biomass per unit area (g/m^2). Yield was obtained by plant sampling at the end of season.

Soil water budget method was used to estimate actual crop evapotranspiration (ET). Reference ET_o was calculated using FAO-56 approach with all required meteorological variables secured from an on-site, advanced NOAA weather station. Two WP definitions were quantified in this study, The first is defined by:

$$WP = \frac{Y\ (kg/ha)}{total\ water\ applied\ (m)} \qquad 1$$

where “total water applied” is rainfall plus irrigation. The second WP definition is referred to as normalized WP (WP*; normalized by ET_o for local climate) and was calculated using:

$$WP^* = \left[\frac{B}{\sum\left(\frac{ET}{ET_o}\right)}\right] \qquad 2$$

Where B is aboveground dry biomass per unit area (g/m^2). In Equation 2, the denominator is the unit-less normalized crop ET in the period when dry biomass is accumulated.

Results and Discussion

The maximum air temperature during the growing seasons ranged from 14 to 39 ^{o}C, while minimum air temperature ranged from -1 to 26 ^{o}C. Total solar radiation ranged from 2 to 30 MJ/d/m^2 with reference ET ranging from 1 to 7 mm per day during the three years (Figure 3).

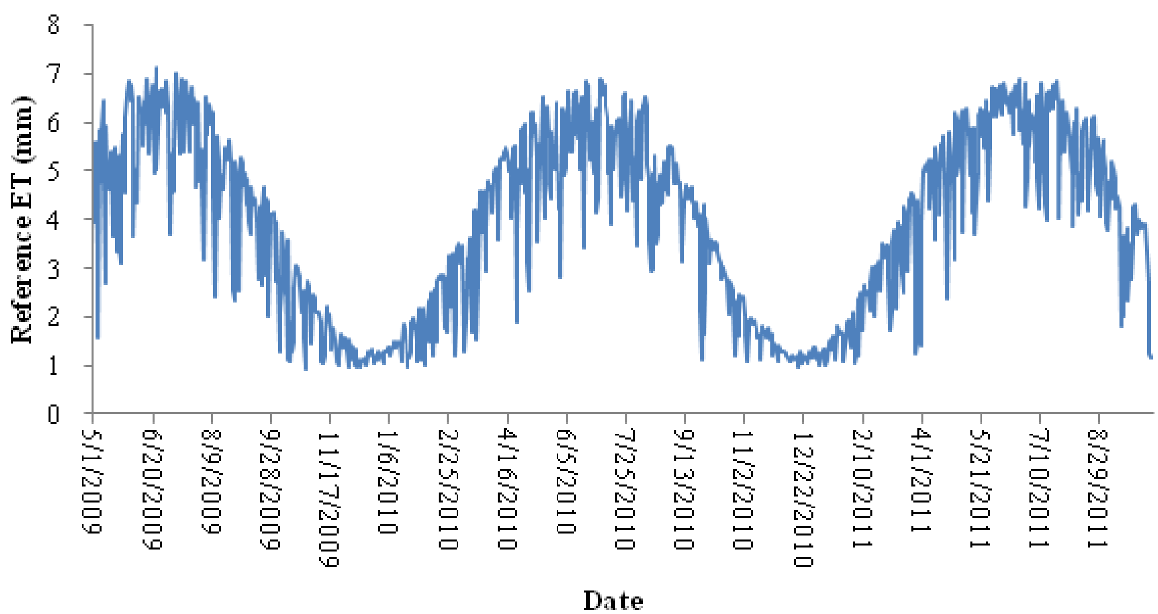


Figure 3.   Daily Reference Evapotranspiration (mm) from May 2009 to October 2011

Total rainfall during the growing seasons was 371 and 544 for 2009 and 2010, with rainfall excluded in the 2011 shelter experiments. Soil water at various depths was averaged to calculate profile SWC of the top 60cm soil. Figure 4 presents trend of profile SWC in field E5 during 2009 for days after planting (DAP).

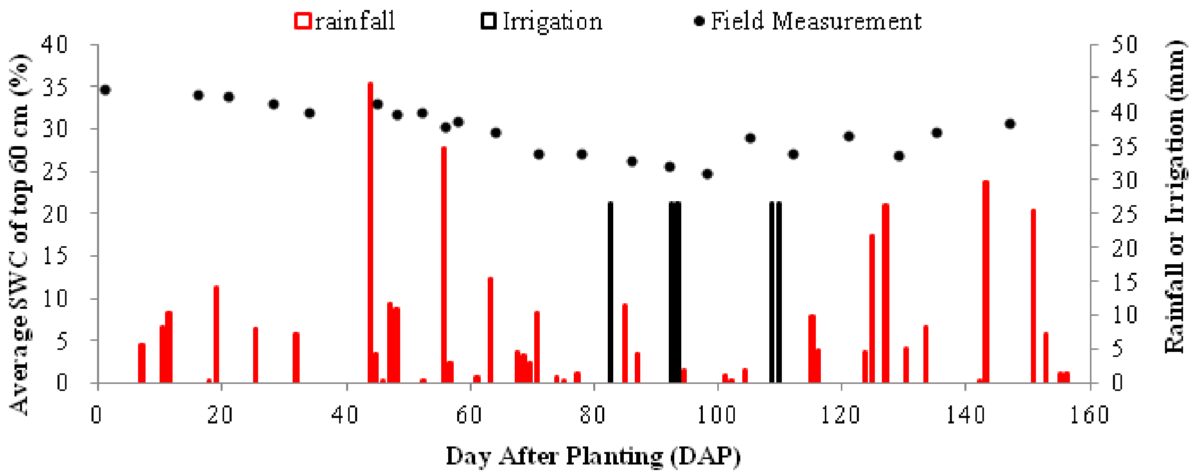
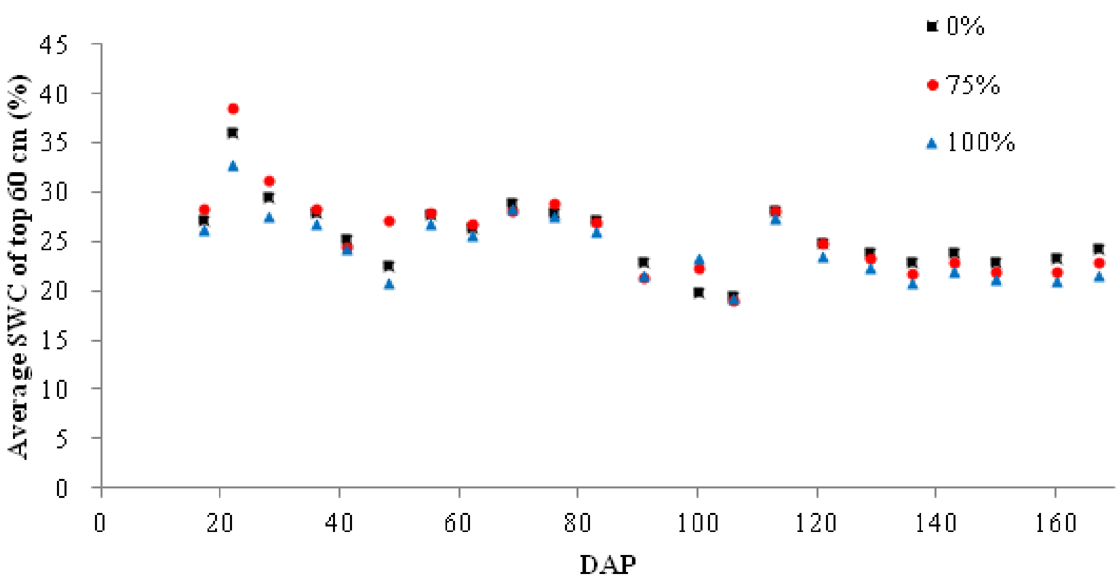


Figure 4. Profile soil water content and irrigation and rainfall amounts at field E5 in 2009

Figure 5 presents the same trend of profile SWC for different irrigation treatments in field E5 in 2010. There were four irrigation events during 2010, with the difference in amount of irrigation applied to 100% and 0% equal to 63 mm. The total rainfall during growing season was 544 mm. which was large enough to reduce treatment effects. Cumulative ET during 2010 growing season was 617, 594, and 538 mm in treatments of 100%, 75%, and 0%, respectively (Figure 5). The difference in cumulative ET among different treatments was mainly due to irrigation. It is noted that cumulative ET for irrigated cotton was less than ET_o by at least 100 mm water.



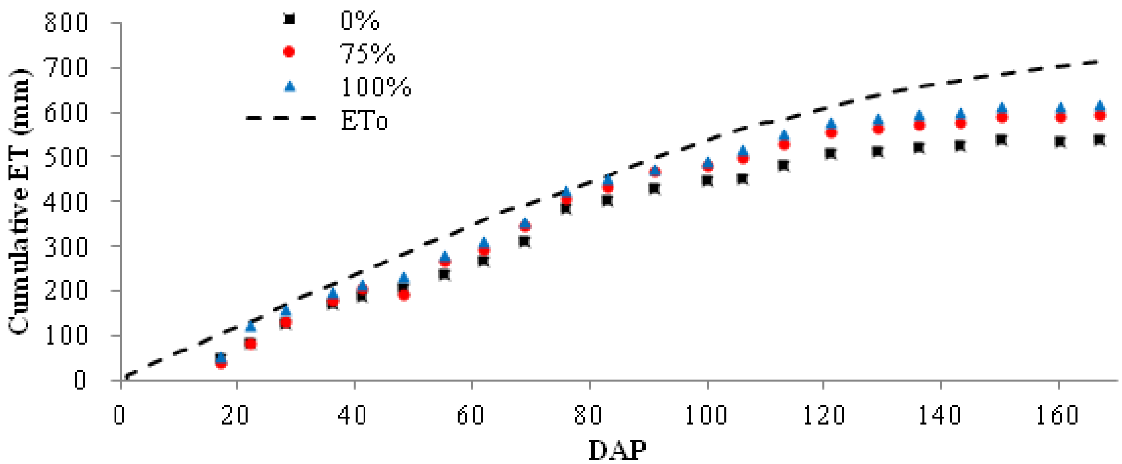


Figure 5. Profile soil water content (top) and cumulative cotton ET (bottom) for the three treatments at field E5 in 2010

Irrigation treatments at the rainout shelter plots started 36 DAP. Volumetric SWC in the sandy Wagram soil varied between a high of 11% and a low of 6%, with the lowest values recorded in the 33% treatment. As shown in Figure 6, cumulative ET for the 100, 66, and 33% irrigation treatments at the shelter were 717, 517, and 321mm, respectively, with the differences mainly due to different amount of irrigation applied and differences in crop canopy size.

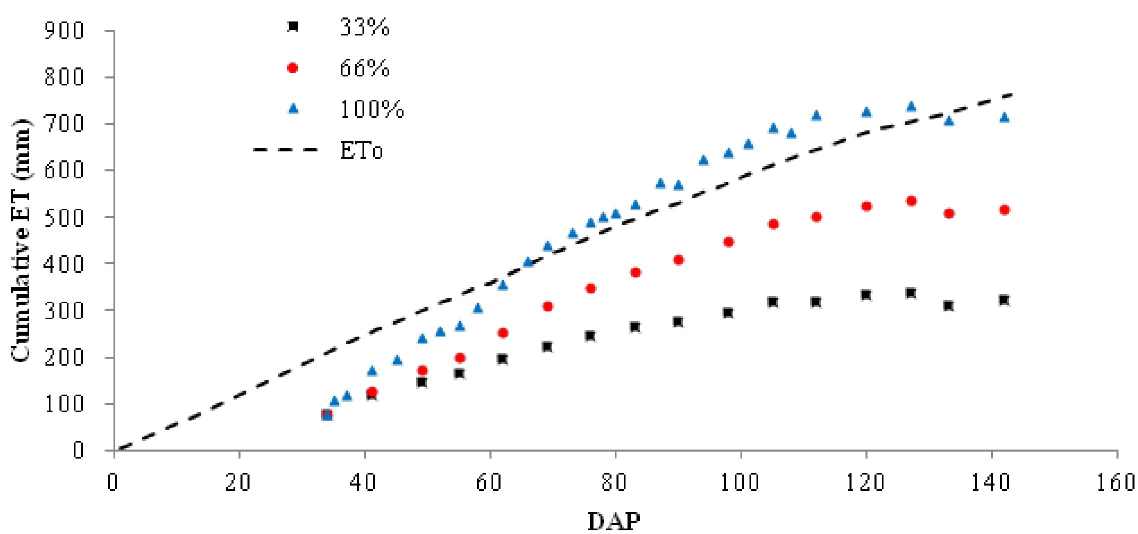


Figure 6. Cumulative cotton ET for the three irrigation treatments at the rainout shelter in 2011

Canopy Cover (CC)

Canopy cover was measured by a digital camera during 2009 in field E5 (Fig. 7). As shown, CC approached maximum values of about 85% by 60 DAP, and senescence started around 108 DAP.

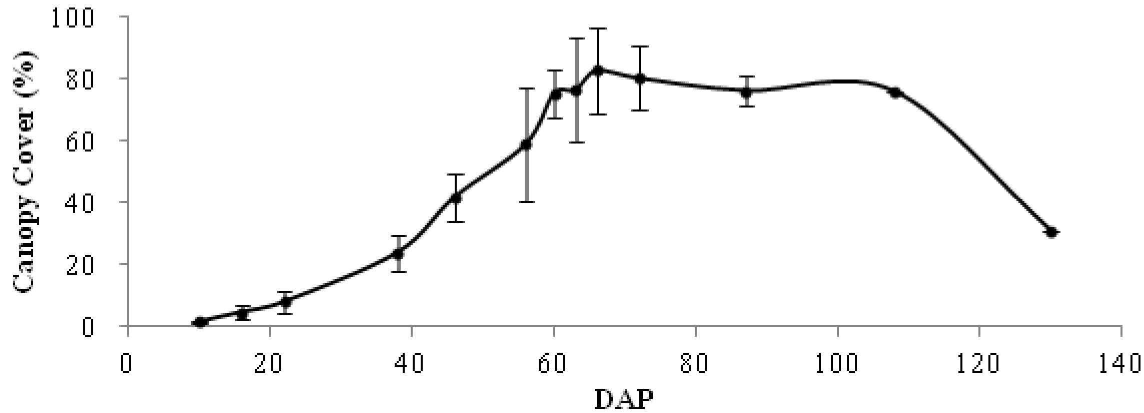


Figure 7. Development of well-watered cotton canopy cover (CC) in field E5 during 2009

In 2010 and 2011, CC was measured both by AccuPAR LP-80 and digital camera at field E5 and at shelter plots. In field E5 during the 2010 growing season (Figure 8), there was not much difference in CC between different treatments. This was mostly because of excess rainfall and lack of prolonged irrigation-induced stress.

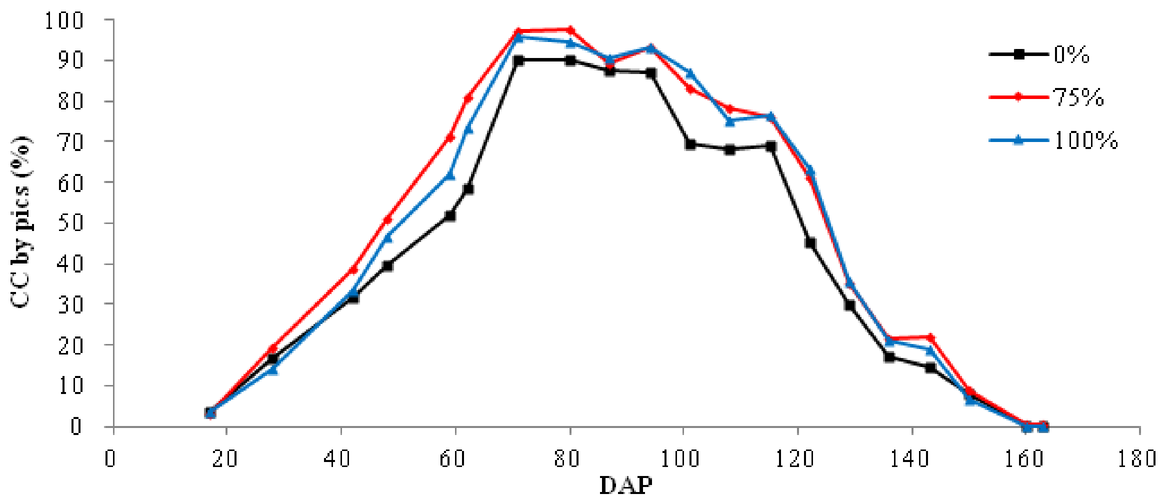


Figure 8. Canopy cover (CC) based on digital pictures for the three irrigation treatments at field E5 in 2010

In the rainout shelter experiment, both 66% and 100% irrigation treatments reached to a maximum average CC of around 85% as measured by PAR, with maximum CC values of 66% for the 33% irrigation treatment (Fig. 9).

PAR measurements were easily affected by cloudiness, and thus such conditions were avoided. Generally, CC measured by PAR decreased at a slower rate during the late season than CC measured by digital pictures. When leaves began senescence and green leaves turned color, VegMeasure software did not register the non-green spots as CC, while PAR accounted for all green and non-green leaves. It is the CC representing the green leaves that is of transpiration consequence, suggesting the utility of a simple digital camera in CC measurement.

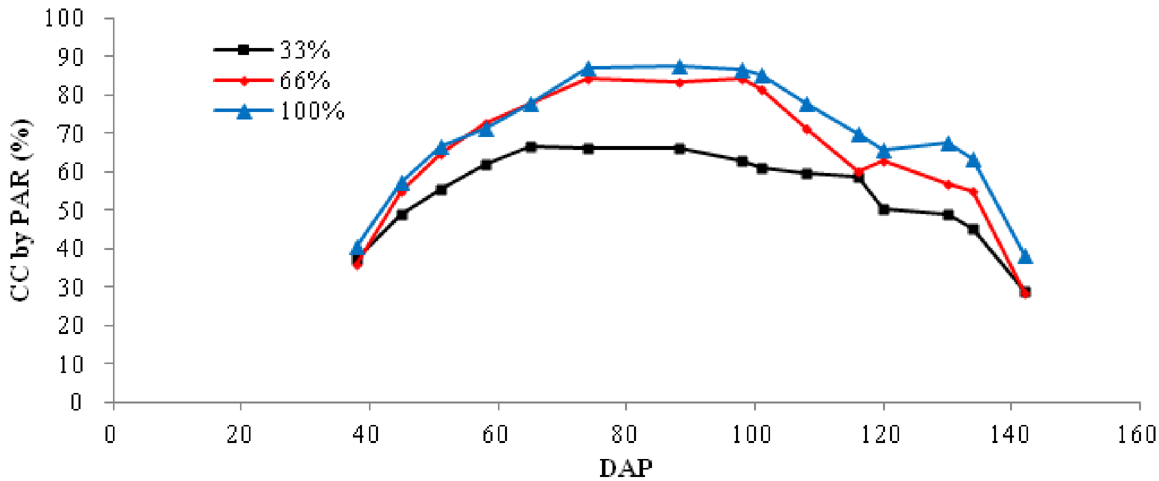


Figure 9. Canopy cover (CC) based on PAR data for the three irrigation treatments at rainout shelter in 2011

Biomass and Water Productivity

For the 2009 field E5 data, normalized WP (WP*) was calculated to be 12.9 g/m^2 by regression of aboveground dry biomass versus sum of ET/ET$_o$ with R^2 of 0.787 (shown in Figure 10).

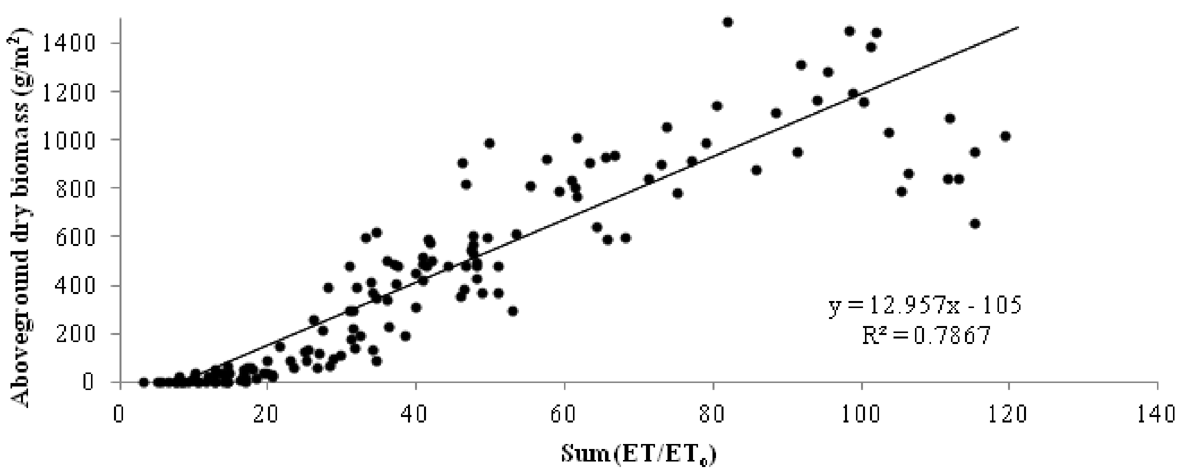


Figure 10. Normalized WP (slope of line) cotton using the 2009 E5 data

In 2010, developments of aboveground dry biomass for different irrigation treatments in field E5 are shown in Figure 11. Up to 90 DAP, there were small differences in aboveground biomass between the three irrigation treatments, but continuously higher values were found for the 75% and 100% treatments after that.

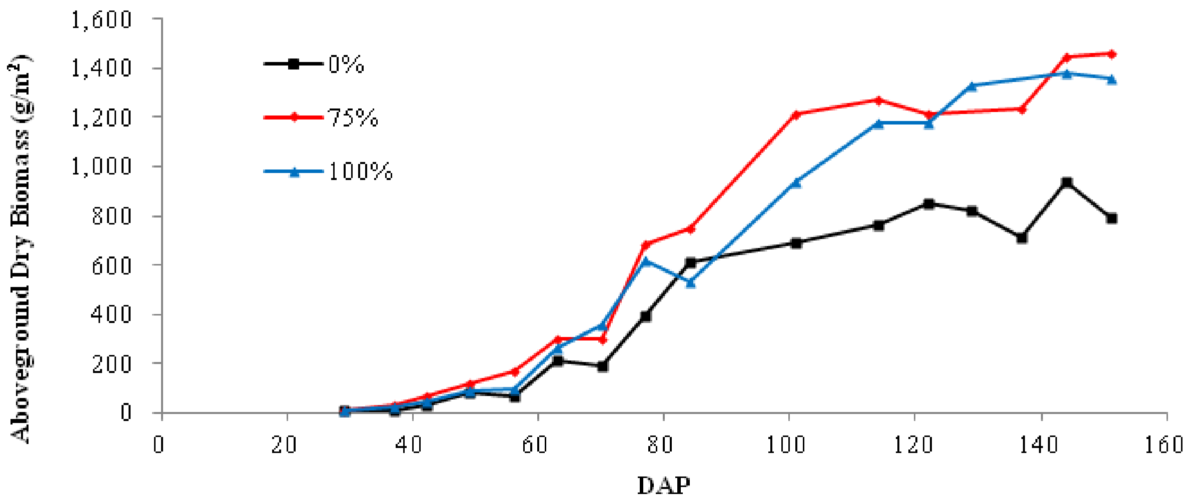


Figure 11. Aboveground dry biomass of cotton under three irrigation treatments in field E5 during 2010

Normalized WP of cotton in 2010 was 12 g/m^2, with an R^2 of 0.646 (Figure 12). Considering the large variability in plant biomass under field conditions, the WP value in 2010 was nearly the same as WP value in 2009 (12.9 g/m^2).

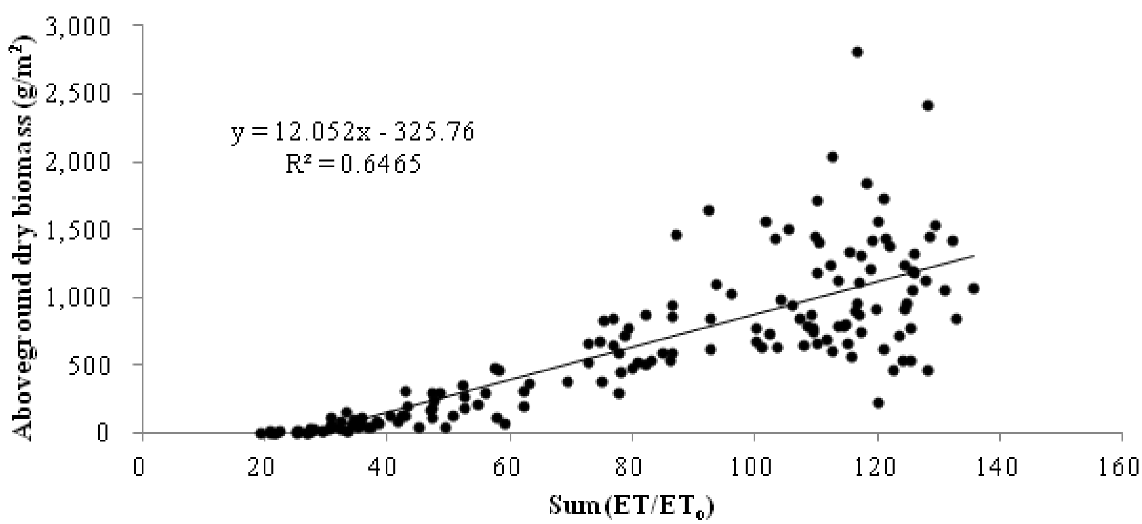


Figure 12. Normalized WP (slope) using the 2010 data at field E5

At the shelter, total aboveground biomass was similar in the 66% and 100% treatments, but substantially lower in the 33% irrigation treatment. Maximum values were 1183 in 33%, 1469 in 66%, and 1392 g/m^2 in 100% treatments, with values in the 33% treatment being consistently lower values than the other two treatments. Normalized WP of cotton in 2011 shelter experiment (Figure 13) was 12.7 g/m^2, which was quite similar to the 2010 value of 12 g/m^2 and 2009 value of 12.9 g/m^2. This apparent constancy of normalized WP (or conservative behavior as discussed in Steduto et al. 2007) is encouraging since it offers a simple biomass or even yield response to water model (i.e., by using a harvest index value).

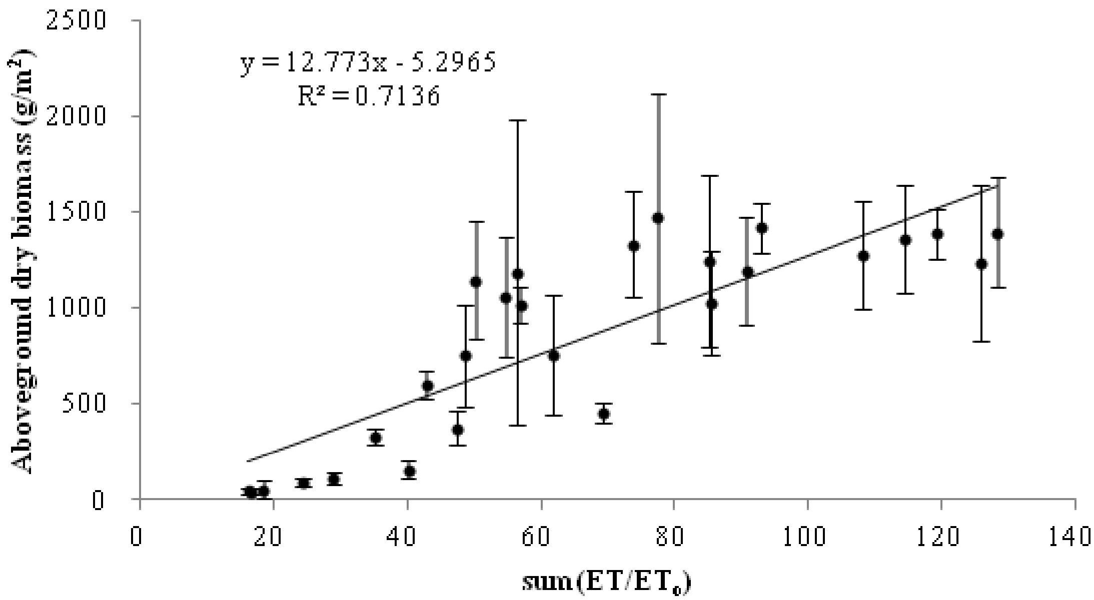


Figure 13. Normalized WP (slope) of 2011 cotton at the rainout shelter experiment

Table 1 summarizes cotton yield, water applied and WP (yield per total applied water) in the three experiments. Statistical analysis showed no significant differences in yields or WP between treatments in 2010. In 2011, yields of the 100% and 66% treatments were significantly higher than those obtained for the 33% treatment. However, there were no significant difference in seed cotton yields between the 66% and 100% irrigation treatments in 2011. As noted, WP values in kg of lint plus seed per m^3 of water applied ranged from 0.53 to 0.71. This range is well within the global range of 0.41-0.95 kg/m^3 reported in Zwart and Bastiaanssen (2004) and also consistent with values reported in Bellamy (2009) and Khalilian et al. (2012) for other cotton varieties in South Carolina. Considering the higher yield and WP values for the 66 and 75% treatments as compared to the 100% treatment suggest advantages to deficit irrigation in cotton. However, we feel that additional seasons of data under a range of irrigation are needed to better understand the behavior of deficit irrigated cotton in the humid regions.

Table 1. Cotton yield (lint and seed), seasonal irrigation, precipitation, and ET amounts, and WP values for the three experiments in 2009-2011

Year/Field/ Treatment	Seed cotton yield	I	P	I+P	ET	WP
	kg/ha	mm	mm	mm	mm	kg/m^3
2009 E5	3489	132	371	503	528	0.69
2010 E5 0%	3091	13	544	556	538	0.56
2010 E5 75%	3682	58	544	602	574	0.69
2010 E5 100%	3315	76	544	620	594	0.53
2011 RS 33%	2134	203	76	305	320	0.70
2011 RS 66%	3591	406	76	508	516	0.71
2011 RS 100%	3671	635	76	711	718	0.52

Note: I = irrigation, P = precipitation. When rainout shelter was operational, rain was not counted (except 76 mm early in season). "WP" values were calculated as yield per total water applied (I+P).

Conclusions

The normalized WP values for cotton under the three experiments were quite the same at 12.9, 12, and 12.7 g/m^2, with an average value of 12.5 g/m^2. These values are lower than literature suggested WP value of 15 g/m^2 for C3 plants, but not too far off considering that we used ET in place of T in Equation 2. This apparent conservative behavior of normalized WP is encouraging, suggesting the use of normalized WP as a simple biomass model which can be equally a yield model by using an expected value for cotton harvest index. The utility of this simple model can be recognized in predicting yield response to deficit irrigation and drought stress. Future work in this area is suggested herein.

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Water Productivity of Cotton in the Humid Southeast - FAO AquaCrop Modeling

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Abstract: *Robust crop models help complement field experimentation and predict the impact of alternate management on production. Recently, the Food and Agriculture Organization (FAO) of the United Nations developed the AquaCrop, a yield response to water stress model. AquaCrop has been parameterized for a number of crops, but not for cotton in a humid region. Using field data, AquaCrop was parameterized and tested for cotton under both open field and a rainout shelter at the Clemson University, Edisto Research and Education Center, near Blackville, SC. Parameterization was less demanding than expected, requiring adjustments of a few model parameters. Using the parameterized model with independent field data, the model simulated canopy cover, soil water content, and cumulative ET values that were highly correlated with measured values with coefficient of determination (R^2) values greater than 0.79. The properly parameterized AquaCrop provides the necessary tool to study irrigation optimization under intermittent drought stress and climate variability in the humid Southeast.*

Keywords: AquaCrop, Water Productivity, modeling, cotton, evapotranspiration, irrigation

Introduction

Simulation models have been used for decades to analyze crop responses to environmental stresses and to test alternate management practices. Modeling complements field experimentation and help limit lengthy and expensive field tests. Crop yield response to water has been framed in a few simple equations in the past, while more sophisticated simulation models have been developed in recent decades. The tradeoff between simplicity and accuracy of the models remains an issue of concern if their broad application is to be achieved. Model has to be simple enough to be comprehensible by others, but complex enough to be comprehensive in scope (Monteith, 1996).

Recently, the Food and Agriculture Organization (FAO) of the United Nations addressed this concern by developing the AquaCrop model. AquaCrop evolved from the basic yield response to water algorithm in FAO Yield Response to Water (FAO-33) to a daily-step, process-based crop growth model with limited complexity than other models (Raes *et al.*, 2009; Steduto *et al.*, 2009; Todorovic *et al.*, 2009).

AquaCrop was recently tested for various crops, including cotton, across a wide range of climate, soil types, water deficit, and management conditions (Farahani *et al.*, 2009; Geerts *et al.*, 2009; Hsiao *et al.*, 2009; Karunaratne *et al.*, 2011; Salemi *et al.*, 2011; Stricevic *et al.*, 2011; Zeleke *et al.*, 2011). The model did a good job of simulating canopy cover, yield, and water productivity. AquaCrop simulated well Bambara groundnut with field observations originating in three zones in semi-arid Africa with R^2 values of 0.88, 0.78 and 0.72 for the canopy cover (CC), aboveground dry biomass (B), and yield (Y), respectively (Karunaratne *et al.*, 2011). Farahani et al. (2009) tested this model for cotton under Mediterranean climate, resulting in accurate prediction of ET (<13% error), canopy cover (9.5% error) and yield (<10% error). Salemi et al. (2011) used AquaCrop to study winter wheat yield performance under deficit irrigation in an arid region. However, the transferability of the existing cotton parameters developed in Mediterranean environments to humid climate with different climate regimes, soils, irrigation methods, and field management is unknown. Hence, our objectives were to parameterize and validate AquaCrop for cotton growth in the humid Southeast U.S.A.

Material and Methods

Site Condition

Data used for modeling purposes were detailed in Qiao (2012) and in a companion paper (Farahani et al., 2012; in this proceedings). Three irrigated cotton experiments were conducted at Edisto Research and Education Center of Clemson University (EREC), Blackville, SC. In-season variations in cotton growth parameters and water use as well as water productivity (WP) were quantified under different irrigation regimes ranging from dryland (i.e., no irrigation) to full irrigation. The climate is subtropical with hot and humid summer and mild to chilly winter. Annual precipitation is abundant, ranging from 1000 to 1700mm, while drought and excessive rainfall make it hard for irrigation management. Rainfall distribution in the Southeast U.S.A. is very uneven. For example in South Carolina, there is a probability that in one out of three years, a twenty one consecutive day period during the growing season will occur with total rainfall of less than 53mm; and every year a period of fourteen days will occur with total rainfall of less than 35mm (Linvill, 2002). An automated weather station inside the research center measured daily values of minimum and maximum air temperature and relative humidity, precipitation, solar radiation, and wind speed at 2 m height. Daily reference evapotranspiration (ET_o) was computed using the Penman-Monteith approach (Allen *et al*., 1998).

AquaCrop Modeling

AquaCrop was first parameterized using the cotton datasets from 2011 experiment under an automatic rainout shelter (2011 RS for short) and from 2009 experiment at E5 field (2009 E5 for short), The model was then validated using an independent dataset from the 2010 cotton experiment at E5 field (2010 E5). This study used the AquaCrop V3.1. AquaCrop requires the input data files for climate, crop, soil, irrigation, and initial soil water (SW_{ini}) conditions, which were assembled using the field data described above

Model parameterization was performed with two datasets (2009 E5 and 2011 RS) by first matching the measured and simulated canopy cover of fully irrigated cotton crop (2009 E5 data and the 100% irrigation treatment data in 2011 rainout shelter). This procedure was repeated to ensure model predictions of ET, biomass, and yield were satisfactory. Default parameters from AquaCrop were initially used. Default parameters were adjusted based on the results from the above adjustment steps. The model was also parameterized in 2011 based on simulation results of deficit irrigation treatments (33% and 66% of full irrigation). Trial and error approach was used until satisfactory results were gained.

Upon parameterizing the model, the model was validated using the independent 2010 dataset from E5 field. To evaluate AquaCrop performance, a linear regression was used to determine correlations between the observed and simulated values of CC, B, seasonal ET, and yield.

Results and Discussion

Model Parameterization – 2009 E5 and 2011 RS

Adopting a trial and error approach, changes were made to the default parameters from Cordoba, Spain for cotton. Table 1 shows default parameters of cotton as suggested by AquaCrop.

Table 1. Default parameters based on cotton data from Cordoba, Spain

User Adjusted	Units or meaning	Value
	Development parameters	
CGC	increase in CC relative to existing CC per GCD, %	10
CDC	decrease in CC relative to existing CC per GCD, %	2.9
CCx	Maximum canopy cover, %	98
Kcb	Crop coefficient when canopy is complete but prior to senescence (Kcb,x)	1.1
Zx	Maximum effective rooting depth, m	1.2
	Water stress response parameters	
$P_{exp,upper}$	as fraction of TAW, above this leaf growth is inhibited	0.2
$P_{exp,lower}$	as fraction of TAW, leaf growth completely stops at this point	0.7
f_{exp}	shape of expansion curve, the bigger the more resistant to stress	3
$P_{sto,upper}$	as fraction of TAW, stomata begin to close at this point	0.65
f_{sto}	shape of stomatal curve, the bigger the more resistant to stress	2.5
P_{sen}	as fraction of TAW, canopy beging to senescence at this point	0.75
f_{sen}	shape of senescence curve, the bigger the more resistant to stress	2.5
	Crop production parameters	
WP	Water productivity, g/m^2	15
HI_o	Reference harvest index, %	30

Note: CGC is canopy growth coefficient. CDC is canopy decline coefficient. GCD is growth calendar days. $P_{exp,upper}$ and $P_{exp,lower}$ are the upper and lower threshold of soil water depletion factor for canopy expansion, respectively. f_{exp} is shape factor for water stress coefficient for canopy expansion. $P_{sto.upper}$ is the soil water depletion factor for stomata control. f_{sto} is shape factor for water stress coefficient for stomata control. P_{sen} is the shape factor for water stress coefficient for canopy senescence and f_{sen} is the shape factor for water stress coefficient for canopy senescence. Reference Harvest Index (HIo) is the ratio of the yield mass to the total aboveground biomass that will be reached at maturity for non-stressed conditions.

Canopy Cover (CC)

As pointed out in Farahani et al (2009), correct simulation of CC is central to AquaCrop performance, as it affects the rate of transpiration and consequently biomass accumulation. After parameterization, CGC was increased to 12% from the default value of 10% and CDC was increased to 6.3% from the default value of 2.9%. The water stress response parameters were then adjusted where $P_{exp,upper}$ was changed from 0.2 to 0.4 and f_{exp} was changed from 3 to 3.5. For the period of senescence, $p_{sen,upper}$ was changed to 0.8 from the default of 0.75. Figure 1 shows simulated versus measured CC both by AccuPAR LP-80 (Decagon Devices, Inc.) and digital camera. As shown, AquaCrop did a good job of simulating CC for the 66% and 100% irrigation treatments. AquaCrop overestimated CC beyond 51 DAP (Day After Planting) for both 33% and 66% treatments. Between 51 DAP and 82 DAP when canopy was still developing, $p_{exp,upper}$ must have been reached, and therefore, plant could not reach the maximum CC. Also, from 82 DAP to the end of season, p_{sen} was reached so simulated CC declined faster than measured values. Similar results were reported by Heng et al. (2009) in which simulated CC declined faster than measured CC values for nonirrigated treatments. They concluded that AquaCrop was not able to simulate slowing down of the stress-induced early senescence when there was rainfall or irrigation. Also, it could be seen that the model tends to overestimate CC later in season for the 100% irrigation treatment. This could be related to the nature of PAR measurement. Compared to maximum average CC measured by digital camera, maximum average CC measured by PAR was lower.

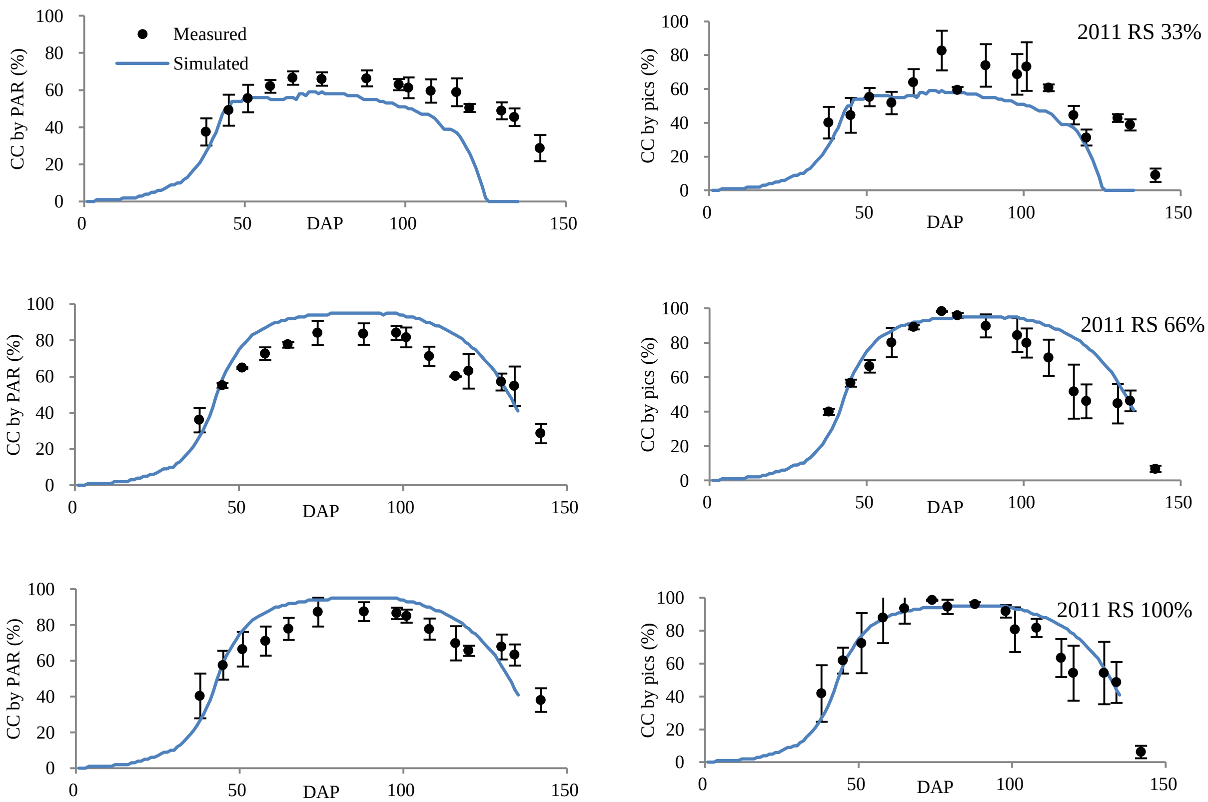


Figure 1. Comparison of simulated versus measured CC for 2011 RS and 2009 E5 experiments (continuous lines are predicted values)

Evapotranspiration (ET)

Crop ET is directly related to canopy cover. After simulating CC successfully, simulated ET values were compared to measured ET values. AquaCrop is able to segregate ET into soil evaporation (E) and crop transpiration (T_r). However, soil evaporation is hard to measure in the field using current equipment, so the total of soil evaporation (E) and crop transpiration (T_r) was used in this study. In AquaCrop, Tr is calculated as:

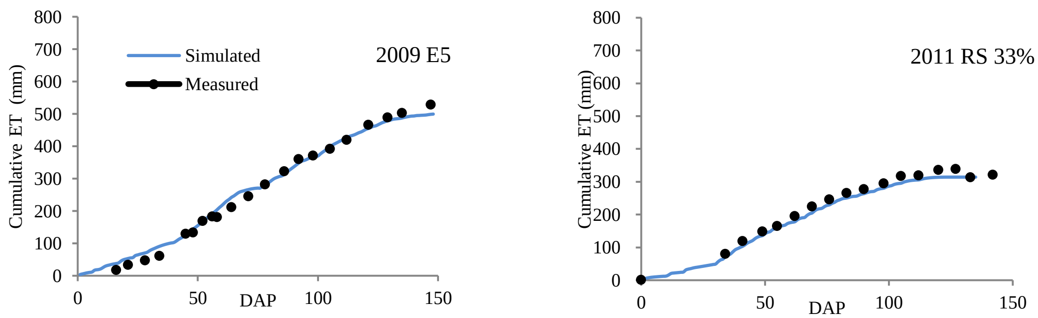
$$Tr = Kcb * ET_o \; with \; Kcb = (CC^* \times Kcb_x) \qquad 1.$$

Where Kcb is crop coefficient, ET_o is reference evapotranspiration, Adjusted CC is denoted as CC^*, and Kcb_x is the crop coefficient when canopy is fully developed. When there is water stress, transpiration is adjusted by a stress factor as:

$$\text{Tr} = Ks_{sto} \times CC^* \times Kcb_x * ET_o \qquad 2.$$

Where Ks_{sto}, Ks_{exp}, and Ks_{sen} are the stress coefficients for stomatal conductance, canopy expansion, and canopy senescence, respectively. The range of these coefficients varies between 0 and 1 depending on how much water is depleted. Only Kcb was changed during the process of parameterization, from a value of 1.1 to 1.2 based on Bellamy (2009) who reported that the crop coefficient for cotton in South Carolina was about 1.24 for mid stage. Figure 2 shows simulated cumulative ET versus measured ET for 2009 E5 and 2011 RS experiments.

Cumulative ET was successfully simulated for 2009 E5, 2011 RS 33%, and 2011 66% which correlated with measured cumulative ET with R^2 of 0.995, 0.994, and 0.996, respectively. While for 2011 RS 100%, simulated cumulative ET correlated with measured cumulative ET with an R^2 of 0.984, the seasonal ET value was 150mm less than measured ET. From AquaCrop output, the model did simulate 104mm drainage through the season. Also, it was possible the shelter failed to move on DAP 128 while the rainfall was 61mm on that day. These two values could add up to 165mm, which could explain the deep seepage of 150mm as predicted by the model. Drainage was expected to be near zero during this experiment under the carefully irrigated drip irrigation, but a few long irrigation durations of the sandy soil could have caused deep seepage.



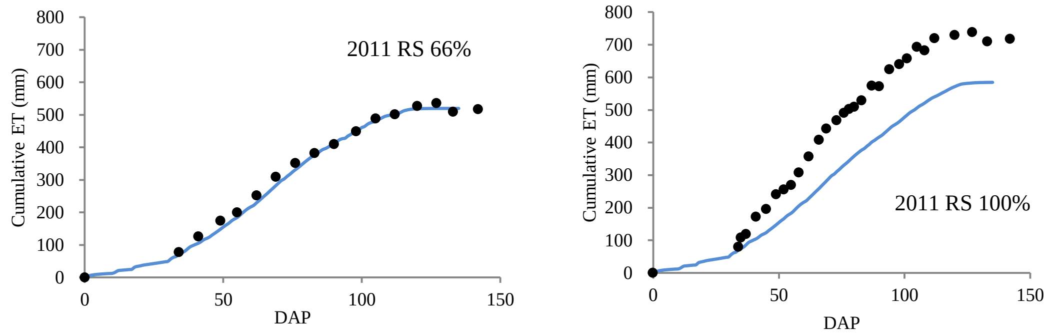


Figure 2. Simulated ET versus measured ET for 2009 E5 and 2011 RS experiments

Aboveground Biomass and Yield

After modeling ET, simulated and measured values of biomass were compared. As stated above, biomass is calculated in AquaCrop using equation

$$B = WP \times \sum\left(\frac{Tr}{ET_o}\right) \qquad 3.$$

Water productivity (WP) is the key parameter in yield and biomass computation in the model. It is normalized by climate condition. Crops could be classified into different groups (C3 and C4) with WP values that are nearly twice as large in the C4 than in C3 plants. For C3 crops, literature suggests WP values between 15 to 20 g/m^2. For C4 crops, WP values of 30 to 35 g/m^2 are suggested. WP could be adjusted based on soil fertility level. For this study, the fertility level in all experiments was not limited, thus no simulation of fertility effects was performed.

Simulated biomass values were compared with measured values in different treatments and years (Figure 3). The measured WP values for cotton under the three experiments were 12.9, 12, and 12.7 g/m^2, which were not only similar, but also close to model suggested WP value of 15 g/m^2 for cotton. It should be pointed out that due to the difficulty of separating soil evaporation and crop transpiration (T_r), the calculated WP values were possibly lower than real values when using ET in place of T. Also, large variation in biomass sampling could also induce errors in WP determination. For modeling, the value of WP was adjusted to 14.5 g/m^2 to account for the fact that we used ET in the WP estimation while the model is interested in WP values based on transpiration (or T_r). AquaCrop simulated biomass accumulation rather well for 66% and 100% irrigation treatments in 2011, as well as for the 2009 E5 cotton experiment. The model underestimated aboveground biomass for 33% irrigation treatment in 2011 rainout shelter experiment. This could be the result of the underestimation of canopy cover for the same treatment, as previously shown in Figure 1.

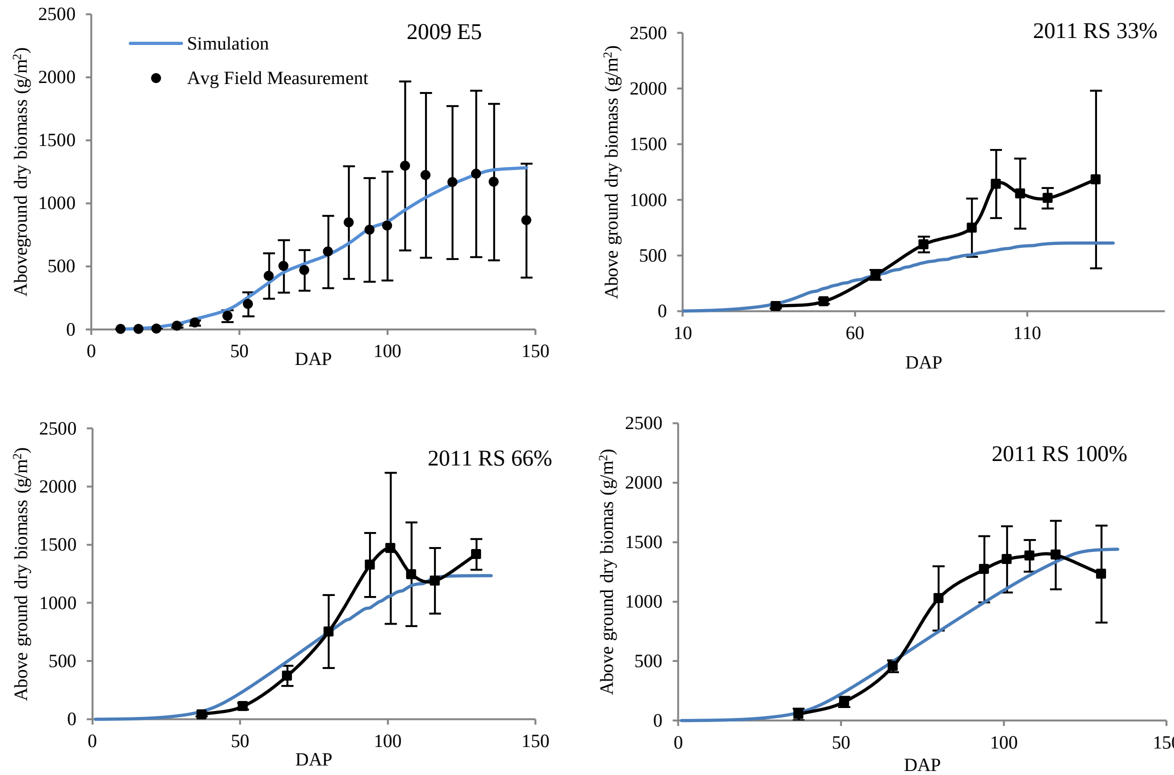


Figure 3. Simulated versus measured aboveground dry biomass

The partition of biomass into yield is simulated by equation:

$$Y = B \times HI \qquad 4.$$

Where HI is harvest index. HI could be adjusted by water stress, failure of pollination, and inadequate photosynthesis based on HI_o (reference harvest index). In order to clearly control the parameterization process, water stress effect was only considered in canopy cover development. No stress was induced to harvest index. However, in an effort to ensure correct simulation of the final yield, reference harvest index was slightly adjusted to 27% from the default value of 30%. The regression coefficient of simulated versus measured yield values was 0.909, suggesting satisfactory performance by the model (Figure 4).

Validation of AquaCrop

After successful parameterization of Aquacrop for cotton using the 2009 E5 and 2011 rainout shelter datasets, the model was validated using the independent dataset of 2010 cotton experiment at E5 in terms of canopy cover, ET, aboveground dry biomass, and yield. Table 2 presents a complete list of Aquacrop crop parameters for cotton grown in the humid region experimented in this study.

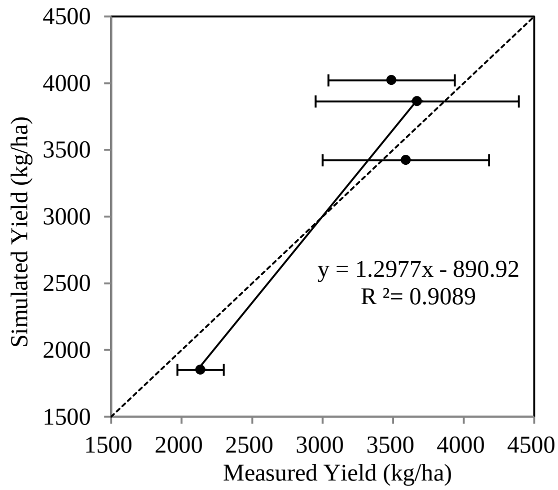


Figure 4. Simulated versus measured yields (seed + lint cotton) for 2011 shelter and 2009 E5 experiment.

Table 2. Parameterized crop parameters for cotton

User Adjusted	Units or meaning	Value
	Development parameters	
CGC	increase in CC relative to existing CC per GCD, %	12
CDC	decrease in CC relative to existing CC per GCD, %	6.3
Kcb	Crop coefficient when canopy is complete but prior to senescence (Kcb,x)	1.2
Zx	Maximum effective rooting depth, m	0.6
	Water stress response parameters	
$P_{exp,upper}$	as fraction of TAW, above this leaf growth is inhibited	0.4
$P_{exp,lower}$	as fraction of TAW, leaf growth completely stops at this point	0.7
f_{exp}	shape of expansion curve, the bigger the more resistant to stress	3.5
$P_{sto,upper}$	as fraction of TAW, stomata begin to close at this point	0.7
f_{sto}	shape of stomatal curve, the bigger the more resistant to stress	2.5
P_{sen}	as fraction of TAW, canopy beging to senescence at this point	0.8
f_{sen}	shape of senescence curve, the bigger the more resistant to stress	2.5
	Crop production parameters	
WP	Water productivity, g/m^2	14.5
HI_o	Reference harvest index, %	27

The validation results show simulated CC values that were well correlated with measured values determined by a digital camera with R^2 values of 0.839, 0.826, and 0.834 for the 100%, 75%, and 0% irrigation treatments, respectively (Figure 5). Simulated CC values were less correlated with measured CC by PAR (R^2 of 0.674, 0.694, and 0.613 for 100%, 75%, and 0% treatments, respectively) simply because PAR measurements do not distinguish between live and senesced and dead leaves.

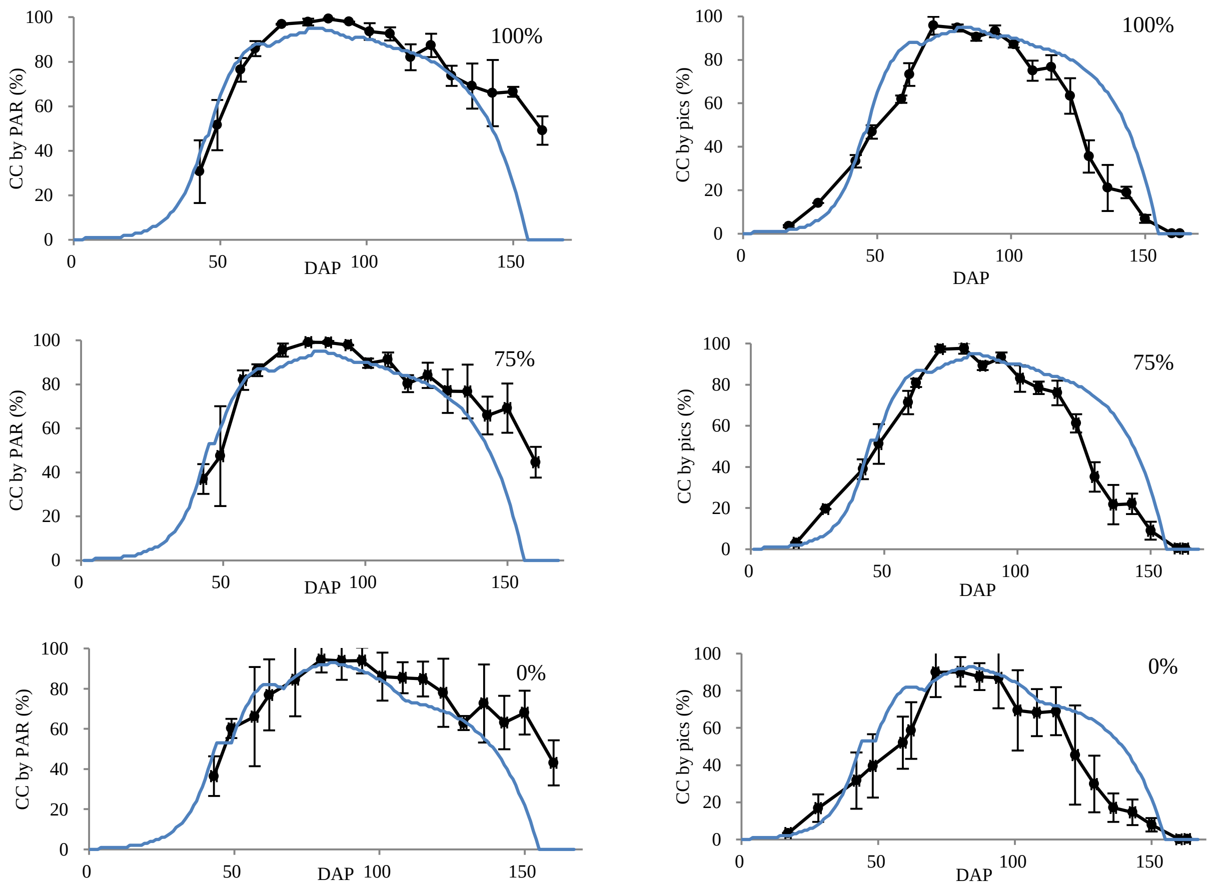


Figure 5. Simulated CC versus measured CC for every treatment of 2010 E5 experiment

As shown in Table 3, the simulated seasonal ET values in the validation run were lower than measured values.

It could be seen that the underprediction of seasonal ET for every treatment correspond to the value of deep percolation simulated by AquaCrop. Since ET was underestimated, final biomass was slightly underestimated except for the dryland plots (0% treatment) (Figure 6).

Table 3. Simulated and measured ET values for 2010 E5 experiment

Irrigation Treatment	Simulated ET	Measured ET	Difference	Model predicted Deep Percolation
	mm	mm	mm	mm
0%	448	538	90	92
75%	500	594	94	112
100%	505	617	112	124

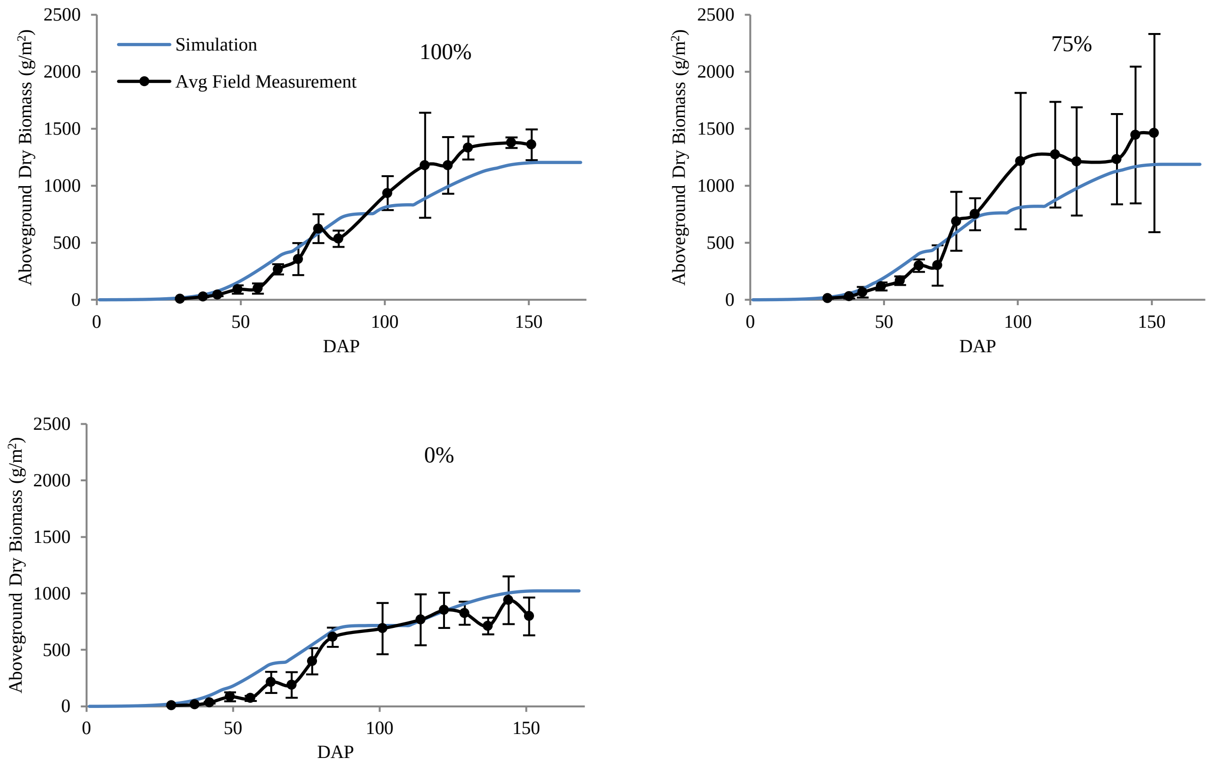


Figure 6. Simulated B versus measured B for every treatment of 2010 E5

Simulated yield values are shown in Table 4, where predictions of the 100% treatment were the most accurate, with least accuracy observed in the dryland treatment. It was questionable that the actual measured yield of 75% irrigation treatment was higher than the 100% irrigation treatment. This could be due to the fact that yields of some cotton cultivars, including the DP 0935, could decrease above certain total water application level (Bellamy, 2009).

Table 4. Simulated and measured yields of 2010 E5

Year	Avg. Seed Cotton Yield	STD. Yield	Simulated Seed Cotton Yield
	kg/ha	kg/ha	kg/ha
2010 E5 0%	3091	254	2356
2010 E5 75%	3682	834	3293
2010 E5 100%	3315	118	3380

Conclusion

The model was successfully parameterized using the 2009 E5 and 2011 shelter data sets, except that calibrating the model to accurately simulate severe water stress or early canopy senescence was difficult. Model performance was satisfactory in terms of CC, aboveground dry biomass, and yield. Simulated ET values were highly correlated with measured values for all experiments, except that the model consistently produced unexpected deep drainage in a number of treatments. We were unable to verify this because of lack of deep soil moisture readings.

Considering the complexity of modeling crop growth and water stress, AquaCrop did a good job of simulating cotton growth and soil water dynamics in the humid Southeast. The parameterization dataset provided in this study applies to cotton grown in the humid conditions similar to South Carolina. South Carolina climate is quite representative of the Southeast, and thus the parameterized model is expected to perform satisfactory in major cotton producing states in the South and Southeast. The parameterized model will be a useful tool for irrigation and water use efficiency studies in this region. Additional studies are encouraged to further test the performance of the cotton parameters developed in this study to ensure their regional applicability and transferability.

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Irrigation Complexities – Using Sensor Networks for Real-time Scheduling in Commercial Horticultural Operations

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Abstract: Since 2009, we have deployed current generation wireless sensor networks in tree farms, container-nurseries and greenhouse operations, working with commercial growers in five States. Irrigation scheduling in ornamental operations is complex, given the large (100 - 500) number of species grown by individual growers. Typically, estimating water use on any given day requires an irrigation manager to rationalize many sources of information, including species water use, plant size and container size (root volume), environmental conditions, and previous rainfall or irrigation applications. It is not surprising that estimates of plant water requirements are often overestimated. Irrigation applications to sensor-irrigated trees were 1.4 to 6.5 times less than applied to grower-irrigated trees during 2012, saving over 16,000 gals of water for a single row of trees, even using precision microsprinkler applications. Over the year, this saved nearly 2/3 of total water applications to this crop. With easy-to-use sensors and software, we are providing real-time information to growers who are scheduling irrigation applications more precisely, greatly reducing water use, reducing various costs and increasing profitability.

Keywords: web-based; sensor networks; decision irrigation; monitoring; control, nursery

Introduction: Automated irrigation scheduling systems are widely-used in intensive horticultural production environments, such as greenhouse, container nursery or field ornamental nurseries. Additionally, many high-value food crops are also irrigated, as are golf-course and high-value landscape settings. Currently, most growers of horticultural crops base their irrigation scheduling decisions on intuition or experience (Bacci et al., 2008; Jones, 2008; Lea-Cox, 2012), using time-based programmable devices, or by using more sophisticated irrigation-scheduling tools such evapotranspiration (E_T) models or soil-moisture sensing devices. Oftentimes, the first question that a grower or manager needs to answer is whether or not s/he needs to irrigate on that specific day. Typically, the next question is how *long* do I need to irrigate, to ensure adequate water is available for the plant? While these questions could seem trivial, plant water requirements vary by species, plant size, season and microclimate, and depend upon any number of environmental and plant developmental factors that need to be integrated on a day-to-day basis. If you then consider the number of species grown in a 'typical' nursery or greenhouse operation (oftentimes >250 species); (Majsztrik et al, 2011), the variety of container sizes (i.e. rooting volume, water-holding capacity) and the length of crop cycles, it quickly becomes obvious why irrigation scheduling in ornamental operations becomes complex, if it is to be achieved with any level of precision (Lea-Cox et al., 2001; Ross et al, 2001).

Although experiential methods for scheduling irrigations can give good results, they tend to be very subjective with different operators making very different decisions. Many times, even experienced managers make an incorrect decision, i.e., they irrigate when water is not required by the plant, or don't irrigate when it is needed. It is also surprising how many so-called "advanced" irrigation controllers which allow operators to program complex scheduling routines merely automate irrigation cycles on the basis of time, without any feedback-based sensor systems. Thus, even with advanced time-based systems, the decision to irrigate is again based solely on the operator's judgment, and the time taken to evaluate crop water use and integrate other information, e.g. weather conditions during the past few days and in the immediate future.

Many sensor technologies have been developed and used over the years to aid irrigation scheduling decisions. Various soil moisture measurement devices are available, e.g. tensiometers, gypsum blocks and meters which directly sense soil moisture (van Iersel, 2012). Additionally, pan evaporation and weather station or satellite forecast data can be incorporated into evapotranspiration (E_T) models, such as the Penman-Monteith model which is widely used in agronomic crops (Fereres et al., 2003), where crop-specific Kc values have been calculated and validated. However, the widespread adoption of most of this technology has not occurred in the nursery and greenhouse industries, for good reasons. Many sensing technologies which were originally engineered for soil-based measurements have been applied to soilless substrates. Many have failed, largely because these sensors did not perform well in highly porous substrates, since porosity is an important physical property that is necessary for good root growth in containers (Bunt, 1961). Even when a technology has been adapted successfully to container culture (e.g. low-tension tensiometers), often the technology has been too expensive for wide-scale adoption, difficult to automate, or there have been precision, reliability and/or maintenance issues. For most growers, initial cost and ease of use are key aspects to the adoption and use of any tool, since they usually don't have the time or the labor to devote to the maintenance of less robust tools.

Sensor Network Hardware and Software: Figure 1 shows the type of wireless sensor network (WSN) that we have deployed in multiple research and commercial sites during the past three years. Decagon Em50R (Decagon Devices, Inc.) wireless nodes are deployed in production blocks, and collect data from a variety of soil moisture and environmental sensors from that specific area. The accumulated data is then transmitted from each sensor node (using a 900 MHz radio card) to a 'base' datastation connected to a personal computer on the farm. The incoming data is collected and stored in a database; software (e.g. DataTrac v.3.5; Decagon Devices, Inc.) then plots and graphically displays the sensor information from each of the nodes. Nodes and production blocks can be organized within the software for ease of access. Incoming data from each node is organized and is appended to the database, and graphically displayed very easily at various time scales, depending on what question the grower/user wants to answer (e.g. what is the current soil moisture status in a particular block/species?). Data from these field nodes can also be transmitted directly to 'cloud' server, using a 3G wireless node (e.g. Em50G, Decagon Devices, Inc.). The logged data is then accessed from the server via a custom website, using the same DataTrac software previously described. In this way, a grower can install and develop a cost-effective and scalable network of sensors that allows for the monitoring of soil moisture and environmental data in real time.

The advantages of these wireless sensor networks are fairly obvious – they provide very specific microclimatic environmental information, which can be expanded to any resolution, determined for a specific production operation, for specific needs. Additional valuable information is also gained from weather station instrumentation using the same network (Lea-Cox et al., 2012),

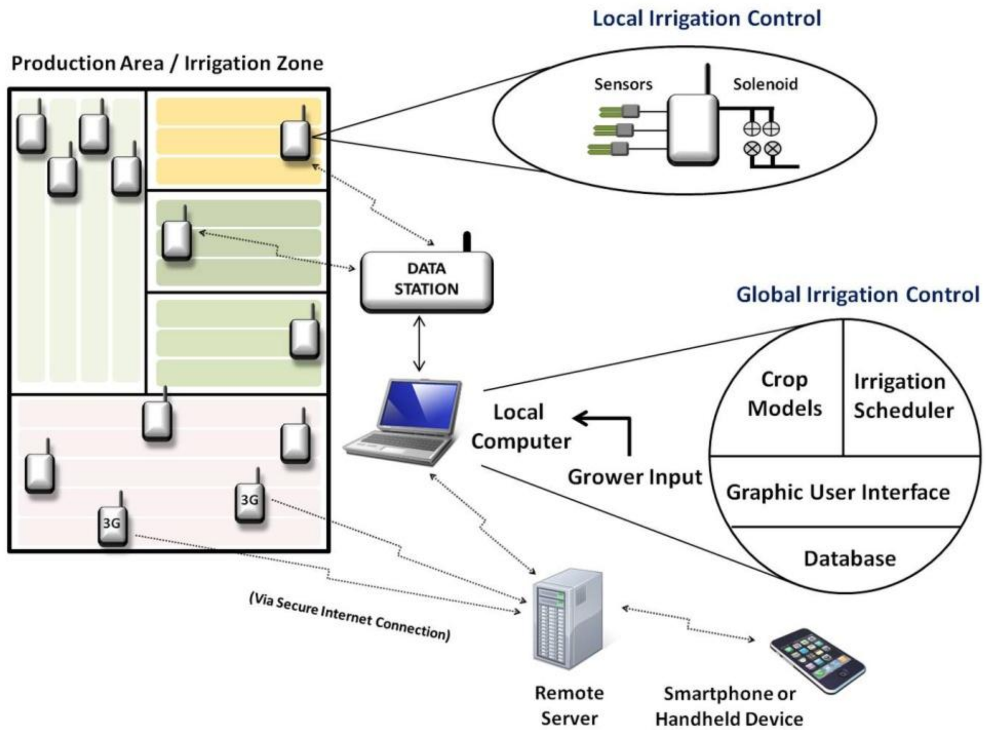

Fig. 1. Schematic of a farm-scale WSN for precision irrigation scheduling (from Lea-Cox, 2012).

including degree-days (integrated pest management), chilling hours (prediction of bud development and flowering) and other various data used for modeling purposes.

Control Node Development: Our project has also developed a battery-operated wireless node (very similar to the Em50R node, called the nR5) which is capable of both monitoring and control. It can operate normal (24V) or latching (12V) solenoids, which greatly increase the utility of these nodes for automatically controlling irrigation events in remote production blocks where there is no power (Kantor and Kohanbash, 2012). Control is achieved by using an advanced software program called Sensorweb (Kohanbash et al., 2011; Kohanbash and Kantor, 2012), which provides a custom website associated with the wireless sensor network on the farm (Fig. 2). The spatial view (homepage) is the first page that users see when they access the Sensorweb interface. This view allows users to see the state of various node locations with a quick glance. The images can be set to display different settings (and colors) by using the list at the bottom right of the page. By simply moving the mouse over an image the user can see more detailed information as well as the current trend for that measurement.

The Sensorweb software (Kohanbash and Kantor, 2012) provides growers with four operating modes: (1) a schedule-based controller very similar to what is commonly used in the industry. Within the schedule, there are two different options to over-ride the schedule to decrease the irrigation time; (2) a local setpoint controller and (3) a global controller. The schedule + local setpoint controller enables the sensor node to make local control decisions based on sensors attached to the node. The schedule + global controller allows the grower to use data from any node in the network, calculated data or model data to control the irrigation and consequently determine if the schedule should be interrupted; (4) The fourth mode is a manual override

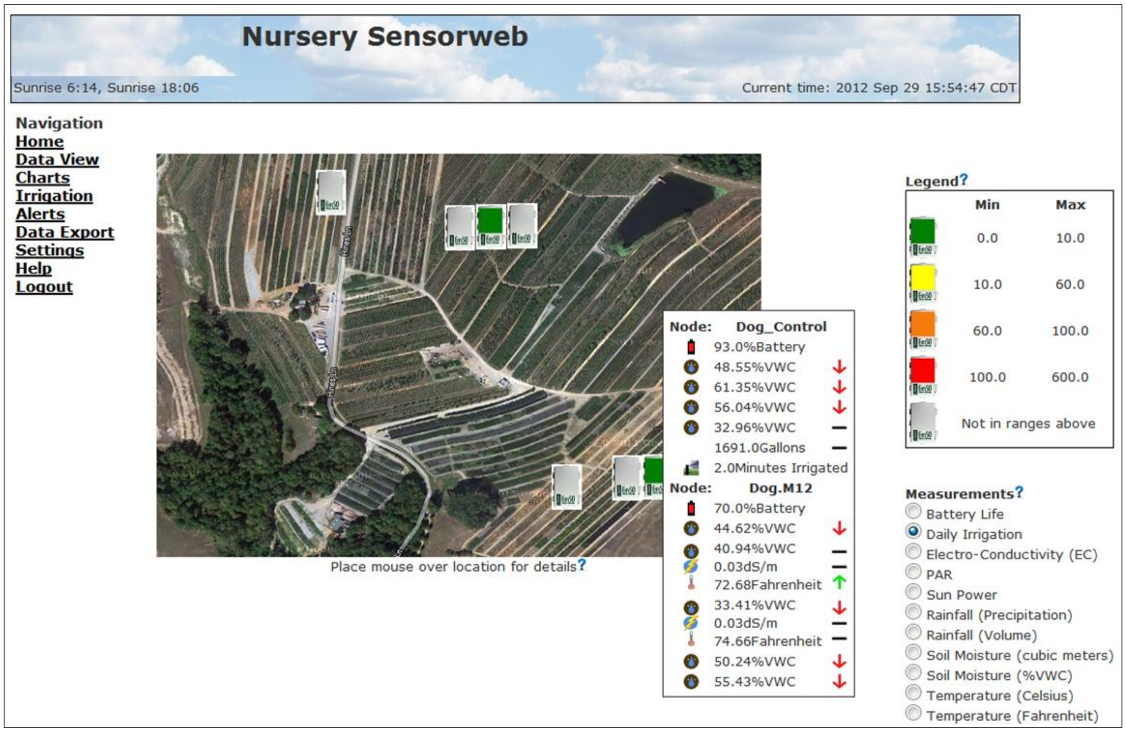

Fig. 2. The Sensorweb homepage for a wireless sensor (on-farm) network in the project.

mode that allows the grower to water in traditional mode, for a given number of minutes. This irrigation scheduling flexibility gives a grower the ability to control how water gets applied to an irrigation zone, with various user-defined parameters. The user can choose between a mode where water will be applied slowly, with small delays between irrigation events which allows water to reach the subsurface sensors (micro-pulse irrigation; Lea-Cox et al., 2009) or a mode in which water is applied continuously for a specified period of time. These modes of action are based on grower preferences and are discussed in detail by Kohanbash et al. (2012).

Sensor-Controlled Irrigation Study: To illustrate the operation and viability of this approach, we highlight some results that we have achieved using local set-point control in a large pot-in-pot container operation in Tennessee during 2012. Briefly, this large (180-acre plus) nursery produces a wide range of trees and shrubs in 10, 15, 30 and 45-gallon containers, and is a major producer of Dogwood (*Cornus florida*). Since container rooting volumes are relatively limited, and because of the pine bark soilless substrate used, irrigation scheduling needs to be much more frequent than with similar species in field soils. Leaching of nutrients from containers is also likely without careful irrigation scheduling. In a comparative study, two separate monitoring and control blocks were installed in March, 2012 – one in a block of Red Maple (*Acer rubrum*) trees, the other in a block of Dogwood (*Cornus florida*) trees (Fig.3a). There were 133 trees in both the control and the monitored rows. The control row in each block was plumbed directly from the mainline to provide independent control by the nR5 node, as shown in Fig 3b. A 12V-DC latching solenoid was installed on the control block, connected to the nR5 node, such that set-point control was enabled (Fig 4). Flow meters (Badger Meter, Milwaukee, WI) were installed on both control and monitoring rows, to provide real-time, cumulative flow data (Fig. 4). The

Fig. 3(a) The *Cornus florida* production block, showing monitoring row (daily cyclic irrigation scheduled by grower) compared to the row controlled by local setpoint control.

Fig. 3(b) The nR5 monitoring and control node, which provides local setpoint (sensor-based) control, in tandem with the 12V-DC latching solenoid (see Fig.4).

grower scheduled all cyclic irrigation events from March through Sept., 2012. An example of this is shown during June (Fig. 5).

Results and Discussion: Typically the grower scheduled 2-4 timed (6-minute) irrigation events every three to four hours during the day during summer. This irrigation frequency decreased to 1-2 irrigations per day during early spring and fall, and irrigations were interrupted for 1-2 days when rainfall occurred. In contrast, the control blocks were only irrigated when an average setpoint of <46.0% volumetric substrate moisture content was sensed by four 10HS sensors (Decagon Devices, Inc.) inserted at a 6-inch depth from the surface of the substrate in four replicate trees. Sensors were inserted horizontally in all trees at this depth, to minimize the variation due to gravitational drainage effects. A custom calibration for these sensors in this specific substrate was done prior to the study, to provide precise volumetric water content readings (data not shown). The micropulse irrigation utility of the sensorweb software was employed (Kohanbash et al., 2011; 2012), such that irrigation events in the control block were pulsed for 2 minutes, with a 3 minute interrupt period between pulse events. In this way, the relatively large amount of water applied by the microsprinkler on each tree (150 mL per minute) could be sensed more effectively by the sensors, such that when the VWC was restored above an average of 46.0%, the irrigation cycle was interrupted. This resulted in much lower leaching from each plant container (data not shown) while minimizing the irrigation cycle times. It should

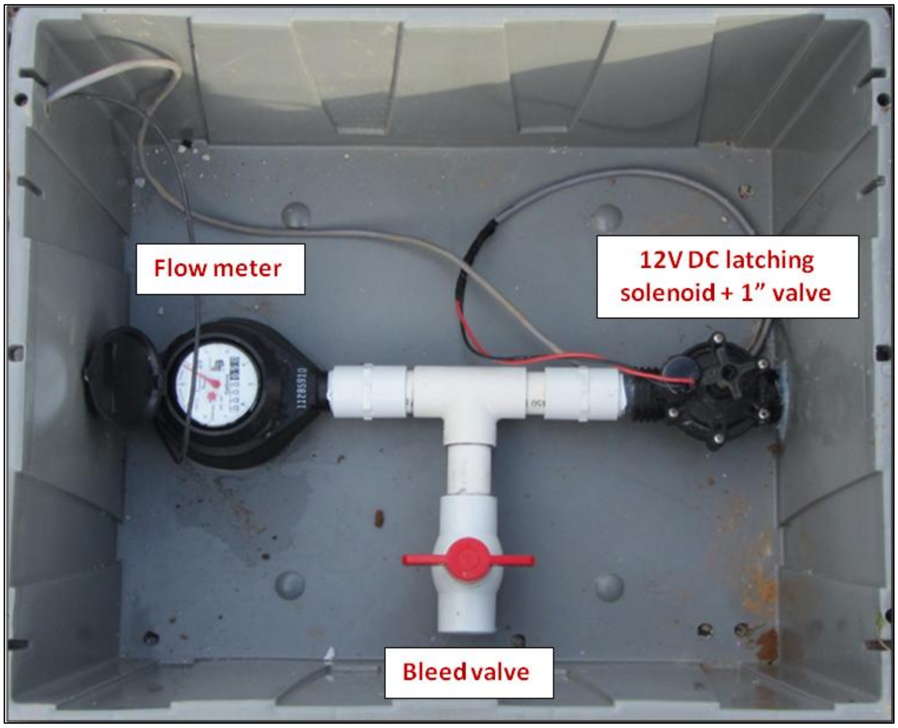

Fig. 4. The 12V-DC latching solenoid installed on the control blocks, wired to the nR5 node, which then initiated irrigations when the average substrate volumetric water content reached a setpoint of 46.0% VWC. The real-time flow meter installation is also shown.

be noted that monitoring and remote control was achieved by the team at the University of Maryland throughout the year, entirely via the website linked to the basestation and the on-farm computer in Tennessee. There were very few times that outside intervention by the grower was necessary, and in those cases, it was merely to make some minor adjustments to sensors.

Two trips were made to the operation during this period to measure the growth rate of the trees and perform minor maintenance on the various nodes in the network (including this block). As can be seen from early summer data shown in Fig.6, the control row trees were irrigated far less frequently than the trees irrigated with a normal cyclic irrigation regime (as shown in Fig. 5). This is significant, as this experienced irrigation manager was not only using his years of experience to supply the trees with adequate irrigation water, but was also following recommended best management practices for minimizing nutrient leaching, and interrupting cycles for rainfall. For the twenty-seven week period (March 24 – September 30, 2012), the average daily irrigation water applied by the grower totaled 1.035 gals / tree, compared to 0.385 gals / tree applied by the sensor-controlled irrigation (Table 1). Weekly average irrigation applications to sensor-controlled trees varied from 1.4 and 6.5 times less than weekly applications to the grower-irrigated trees. However, as of 31 August, there were no significant differences in trunk diameter or height between treatments (data not shown). The sensor controlled irrigation therefore resulted in nearly a three-fold increase in efficiency of water to irrigate these trees (Table 1), without reducing growth or quality of the trees. Similar results were shown for a similar study using a different species (*Acer rubrum*; Red Maple cv. 'Red Sunset') conducted on the same farm and during the same period (data not shown).

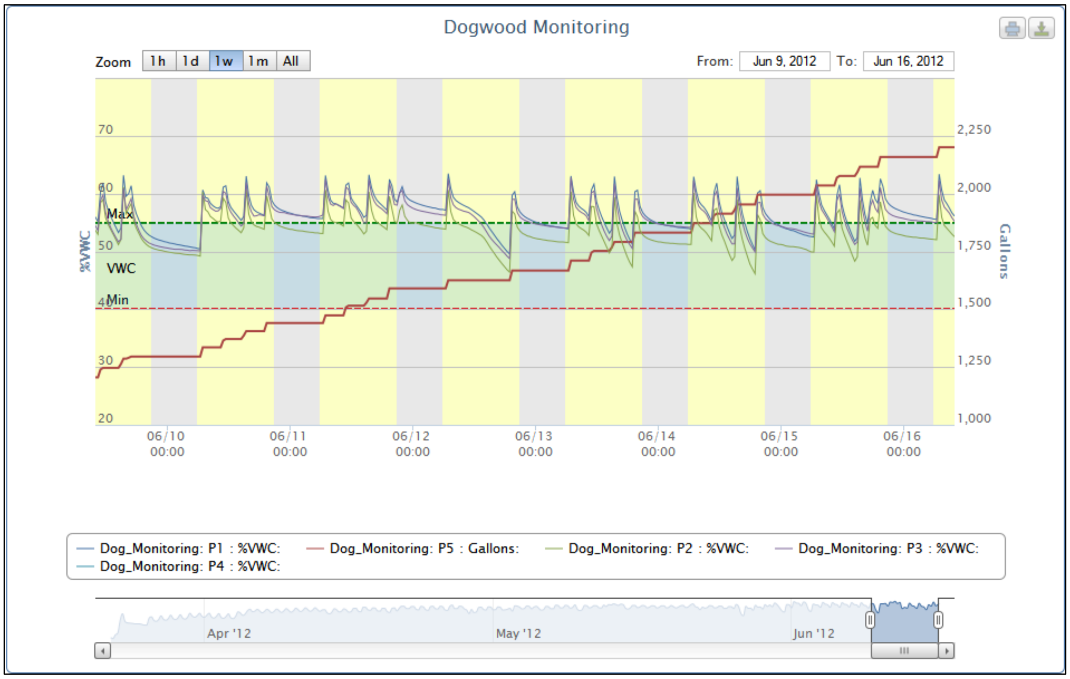

Fig. 5. A graph of substrate VWC from the10HS sensors in four individual trees (left axis) plotted by the Sensorweb software during June, 2012 for the monitored block. The red line indicates cumulative water applied per row of 133 trees (gallons; right axis)

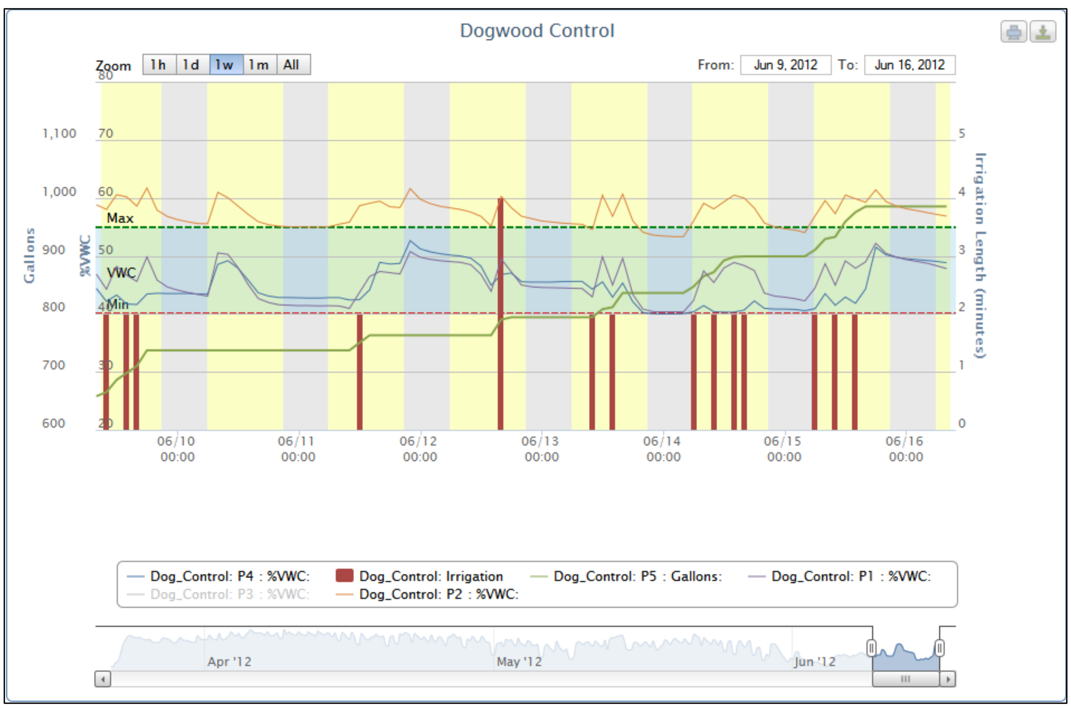

Fig. 6. A graph of substrate VWC from the10HS sensors in four individual trees (left axis) plotted by the Sensorweb software during June, 2012 for the controlled block. The red line indicates cumulative water applied per row of 133 trees (gallons; right axis)

Table 1: Cumulative water use from the monitored vs. sensor-controlled irrigated Dogwood (*Cornus florida*) trees, from 24 March through 30 September 2012.

Irrigation Method	Total Water Use (Gals / Row)	Average Water Application (Gals/ Tree /Day)	Av. Efficiency (Timed vs. Control)	Water Savings (Control vs. Timed)
Grower: Timed, Cyclic	26,025	1.035	0.372	269%
Sensor: Setpoint Control	9,683	0.385		

Conclusions: It is apparent from these results that we can consistently achieve autonomous set-point irrigation scheduling within a commercial nursery operation, using the battery-operated nR5 wireless sensor node. In addition, this autonomous control was achieved remotely through the internet during the six-plus months of the study. Most importantly, we achieved significant water savings with this control in comparison to a very experienced, hands-on irrigation manager, and without affecting the growth of the trees with these reduced irrigation water applications. Additionally, other tangible benefits are resulting from these sensor networks (Chappell et al., 2012; Majsztrik et al., 2012), which will enhance the return on investment to growers in the near future.

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Developing and Integrating Plant Models for Predictive Irrigation

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Abstract. The daily water use (DWU) of ornamental plants can be quantified using sensor-based automated irrigation systems and/or continuous evapotranspiration (E_T) measurement systems. Plant age, container size and environmental factors, such as daily light integral, vapor pressure deficit, and temperature were used in the development of empirical water-use models. Although plant size was the most important plant factor in DWU, daily light integral and vapor pressure deficit were the most influential environmental factors in the day-to-day variation of DWU. We have developed water-use models for several ornamental species, with most of the DWU being explained by plant and daily environmental factors (R^2 > 0.8). With these simple, easy-to-use models, growers may predict water requirements of plants using simple sensor measurements.

Keywords. automated irrigation system, evapotranspiration, daily water use, modeling

Introduction

In ornamental plant production, providing sufficient water on a daily basis is critical to ensure plant quality and continuous growth, and optimize income for growers. However, increasingly limited fresh water resources are facing increased scrutiny from regulators in many states. Agricultural water use is often regarded as the major culprit of unsustainable water use for many reasons including soil salinization, over-extraction of groundwater, and the over-allocation of available surface water supplies (Majsztrik et al., 2011). Therefore, much greater irrigation water use efficiency by agriculture is required to sustain these limited fresh water resources. Efficient irrigation practices may not only decrease costs, but also improve plant quality and yield due to reduce disease and other management issues. For decades, many research studies have been conducted to improve irrigation practices, as a part of best management practices in horticulture industry (Lea-Cox, 2012).

Efficient irrigation systems, such as micro-sprinkler, drip or sub-irrigation can increase uniformity of distribution and also target limited water directly to the root zone, in comparison to overhead sprinkler or travelling gun applications. These systems can improve irrigation efficiency by directly delivering water to the plants, so plants can utilize most of water applied. In addition, only applying irrigation water when required (through precision scheduling) is also critical to increase irrigation efficiency, because if plants do not get sufficient water when they need it, drought stress will reduce yield and crop quality. Likewise, if plants receive excess irrigation water, nutrients can be leached from the root zone and root growth limited by reduced aeration. Understanding plant water use is therefore very helpful, so growers can more accurately schedule irrigation frequencies and the correct amount of water to apply, improving irrigation efficiency.

Currently most irrigation events in ornamental production are scheduled based upon time, with irrigation frequencies determined by grower experience, judged by plant size, development stage, and environmental and other conditions such as rooting volume (Lea-Cox, 2012). Recently developed sensor-based irrigation systems can irrigate plants based on measurements of soil water content and other evapotranspiration (E_T)-based estimates. Automated irrigation using these methods can help reduce unnecessary irrigation on cloudy days, allowing for precise irrigation which maintains the substrate within a good range of available moisture (Jones, 2004). However, in commercial production situations, sensor-based irrigation systems are still quite costly, and sometimes sensors can malfunction or become detached, which then leads to erroneous readings and imprecise irrigation events, unless the grower is alerted to the problem. Therefore, integrating precision irrigation systems with a predictive estimation of plant water use could achieve more efficient irrigation management, saving water, labor and other resources.

Estimates of the required irrigation amount can be based on plant and environmental factors. Plant species, cultivar, and plant size affect daily water use since each cultivar has unique water use characteristics, and plant size affects total transpiration. Environmental factors, such as light, air humidity, air temperature, wind, and soil water availability also affect water use (Jones and Tardieu, 1998). Light is regarded as the most influential environmental factor on water use, since light stimulates stomatal opening and drives photosynthesis. Vapor pressure deficit (VPD), the gradient of water vapor concentration from the leaf to the air, is the physical driving force for transpiration and also affects stomatal regulation. Previously, a number of plant water use models have been developed to predict water use of the plant through the estimation of leaf transpiration and evaporation from the soil/substrate, based on measuring environmental variables.

Mechanistic models that can predict evapotranspiration

The Penmen-Monteith equation is perhaps the most well-known method (Allen et al., 1998) for estimating plant E_T; it predicts net E_T from a crop surface in relation to ambient environmental factors, such as temperature, wind speed, relative humidity, and solar radiation. The Food and Agriculture Organization (FAO) of the United Nations suggests a standard method for modeling E_T, using a modified version of this equation (Allen et al., 1998). The Penman-Monteith equation is an energy balance-based method, and thus it requires good estimates of an empirical crop coefficient (Kc) that incorporates specific features for each crop model. By measuring environmental conditions with a standard weather station, the reference E_T (RET or ET_o; i.e. the evaporation and transpiration from a reference crop under ideal unlimited water supply) can be calculated. By multiplying this reference equation with a crop coefficient (Kc; the multiplier depending on crop species and developmental stage, including leaf area index of the crop), the RET can estimate the potential crop E_T (PET) rate in the field. This equation was developed for field crops with large, uniform canopies and many field crops have relatively well established Kc values. However, Kc values for ornamental plants are highly variable with a large number of cultivars and various growing periods. Accurate modeling with this approach would therefore require a large amount of research to determine these empirical model factors for many different species (Baille et al., 1994).

In general, greenhouse ornamental production is very intensive with short production times; the inaccuracy of Kc for the large number of species grown with relatively fast growth rates, makes it difficult to modify E_T methods for ornamental plant production. Also, various substrates used in greenhouse production are mostly soilless substrates, which typically have much larger particle size and porosities to soils. Soilless substrates therefore require alternative irrigation strategies to field crops (Lea-Cox, 2012).

Quantifying water requirement from automated irrigation system

One of the approaches to measure plant water requirement is to quantify the daily irrigation amount which will maintain the substrate at a moisture level that optimizes plant growth. Our primary objective was to develop an easy-to-use model that describes the water requirements of ornamental plants with easily measured plant and environmental parameters such as plant age, light (photosynthetically active radiation, PAR), temperature and relative humidity. In our study, we used a capacitance sensor-based automatic irrigation system (Nemali and van Iersel, 2006) to maintain substrate moisture content at a stable level, while quantifying the amount of water needed to maintain this on a daily basis, as the crop grew. Using a datalogger system with capacitance sensors, irrigation valves were opened for a short time period (6-10 s) with a frequent irrigation interval (10 min) when the sensor reading was below the minimum substrate water content set point. We used a commercial greenhouse peat / perlite substrate (Fafard 2P; Farfard Company, Anderson, SC) with a volumetric water content set point of 0.40 $m^3 \cdot m^{-3}$. With frequent, small irrigation events, the specific substrate moisture level was maintained without leaching occurring; all the irrigation events were recorded by a datalogger. Using this automatic irrigation system, daily plant water requirements were calculated. Environmental data were simultaneously collected with sensors, and logged including daily light integral (DLI; the total amount of PAR for a day), temperature, relative humidity, and vapor pressure deficit (VPD), to develop plant daily water use (DWU) models, using multiple regression analysis. Plant age and its interaction with DLI, and VPD were used as the variables in the regression model.

In 2009, we developed the DWU models for abutilon and lantana, with 95% and 93% of DWU being explained by these models over the growth of the crop (Kim and van Iersel, 2009). We further developed the petunia DWU model using two cultivars grown in three different container sizes (10, 12.5, and 15 cm in diameter), to investigate the effects of other possible variables. Although two cultivars had slightly different regression models, DWUs of both cultivar were explained by plant age, DLI, VPD, temperature, container size, and interactions between these factors (R^2 = 0.9; Figs. 1A and B from Kim et al., 2011). By partial R^2 calculations, plant age and container size were found to be the most important factors affecting DWU, in that these variables are indicative of plant size. Among environmental factors, DLI was the most important environmental factor affecting DWU.

Load cell systems measuring continuous E_T through changes in weight

Although the water use of container crops with a drip irrigation system can be quantified from observing the leaching of irrigation applications, it is much harder to quantify the water used in sub-irrigation or hydroponic systems using this method. Since these operations are recirculating irrigation systems, leaching is required, and small but frequent irrigations are therefore not suitable. Nevertheless, quantifying the water use of plants with these systems is also beneficial to understand plant water requirements, to avoid unnecessary irrigation or fertigation. Another approach that can be employed in greenhouses is to measure plant DWU with a load cell system. A load cell is a sensor which can precisely measure the weight change of the plant / container system; hourly or daily E_T can then be easily calculated using a datalogger and a simple software program. We installed the load cell system to monitor weight change on an hourly basis, with a 10 min resolution. In this study, 2-6 irrigation events were applied per day. The software calculated the actual E_T from the weight changes after removing the weight changes due to irrigation events.

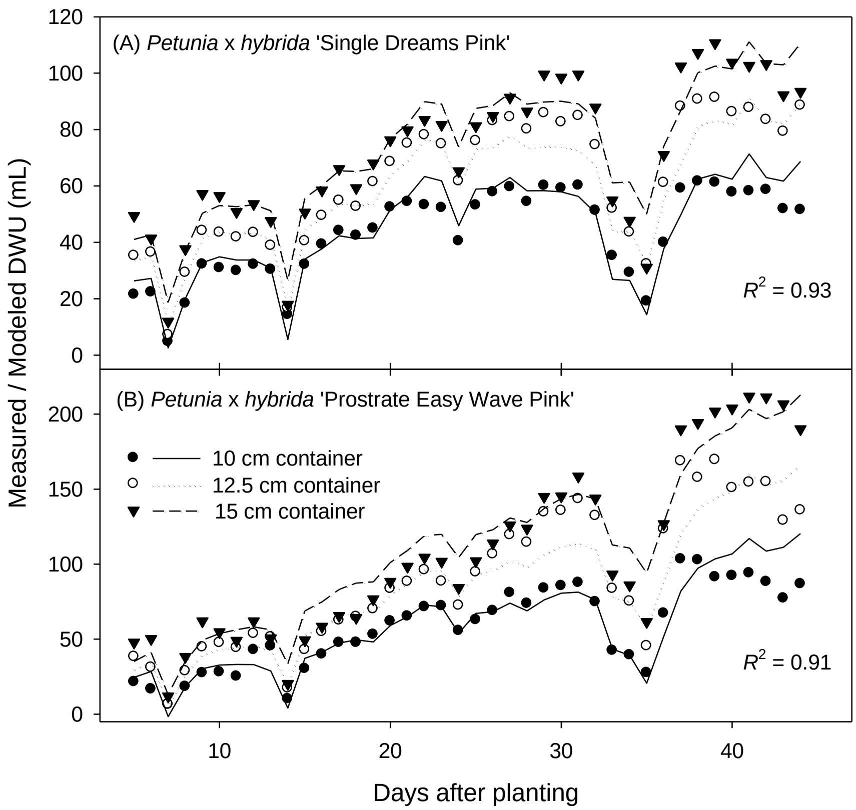

Fig. 1. Measured daily water use (DWU) (symbols) and modeled DWU (lines) of two petunia cultivars grown in three container sizes. The models were based on the effects of plant age (days after planting), container size, environmental conditions, and interactions between DAP and environmental conditions (Kim et al., 2011).

Using this load cell E_T measurement system, DWU models of snapdragon in a hydroponic system were developed (Kim et al., 2012). We conducted this experiment at a commercial cut flower production greenhouse, and simultaneously monitored E_T environmental factors including DLI, VPD, and intercepted DLI. Since cut-flower snapdragon cultivars have tall canopies with large leaf areas, intercepted DLI was selected as a variable which integrates these factors. To acquire intercepted DLI, the light sensors were installed above and below the canopy. A similar regression analysis was performed for the snapdragon DWU model as previously described for petunia, abutilon, and lantana models. Similar to the other DWU models, plant age, intercepted DLI, and VPD were the most significant variables in the snapdragon DWU model. These three variables accounted for nearly 80% of the variability seen between the model and the actual daily change in E_T measured by the load cells. We are still refining the snapdragon DWU model using a slightly simpler approach. To maintain optimal moisture levels in a hydroponic system with a very porous substrate (*e.g.*, perlite), multiple irrigations per day are required. To provide real-time information for scheduling irrigations at a higher frequency, estimating hourly water use will be required. Therefore, our current goal is to develop an hourly water use (HWU) model, which can then be used to more accurately schedule irrigations during the day.

Integration of model in wireless sensor network system

Our group is working on developing integrated irrigation decision support system that includes wireless sensor network with plant water use model components (Lea-Cox et al., 2010). Bauerle and Bowden (2011) integrated MAESTRA (Multi-Array Evaporation Stand Tree Radiation A; a three dimensional process-based model that computes transpiration, photosynthesis, and absorbed radiation within individual tree crowns) for nursery tree crops, and are currently testing this approach. For greenhouse crops, we will integrate our petunia and snapdragon water use models into the Sensorweb software system (Kohanbash et al., 2012), to provide the irrigation decision support for growers. Although our models still need independent validation, these models should provide good information regarding the predictive water use of ornamental greenhouse crops, and assist growers to make better irrigation scheduling decisions.

Acknowledgement

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Sensor Network Deployment and Implementation in Commercial Nurseries and Greenhouses

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Keywords

Wireless sensor network, soil moisture sensor, technology adoption, commercial horticulture production, container production, ornamentals

Abstract

Since testing of wireless sensor networks (WSNs) began in 2009, WSNs have been deployed in a variety of commercial horticulture operations. In deploying these WSNs, a variety challenges and successes have been observed. Overcoming specific challenges has fostered improved software and hardware development as well as improved grower confidence in WSNs. Additionally, members of this collaborative research project have observed growers utilizing WSNs in a variety of ways to fit specific needs; resulting in a variety of commercial applications. Some growers utilize WSNs as fully functional irrigation controllers. Other growers are utilizing components of WSNs to verify grower-controlled irrigation schedules. For example, early adoption of WSNs often begins with implementation of WSNs as irrigation monitoring via WSN software, without utilizing control capabilities. Only after grower(s) become comfortable with software and trusting of the WSN probe's ability to monitor correctly the water content of soilless substrate is WSN control capability instituted.

Introduction

The greatest challenge for many producers, with any technological advance, is the ease with which that technology can be effectively implemented and used. For this reason, our commercial horticulture partners in Georgia (McCorkle Nurseries, Inc. and Evergreen Nursery, Inc.) were selected based on their propensity to be early adopters of technology and their willingness to implement prototype systems within commercial production environments. McCorkle Nurseries is a large, shrub and tree grower, focusing on container sizes between 1 and 25-gallons that are overhead (impact rotors) irrigated. Evergreen Nursery is a mid-sized, groundcover and perennial grower, focusing on container sizes of 1-gallon or smaller that are overhead (impact sprinkler) irrigated.

Design, setup and installation of wireless sensor networks (WSNs) is covered by other 2012 IA proceedings articles and hence will not be discussed here (Lea-Cox and Belyaneh, 2012). However, deployment and implementation of WSNs, with a focus on grower adoption and confidence in WSNs, will be the focus of this article. Deployment and implementation of WSNs at both of the cooperating growers included two phases. In phase 1, initiated in 2009-10, systems were installed at both operations that *only* monitored soil moisture. During this phase, growers had the opportunity to view soil moisture and other environmental conditions (e.g. temperature, relative humidity, vapor pressure deficit) (van Iersel, 2012) graphically via a web-based interface called SensorWeb, developed by Carnage-Melon as part of this project (Kantor and Kohanbash, 2012). SensorWeb, as a monitoring tool, was a valuable resource for growers to determine if too much or too little irrigation was being applied and if irrigation scheduling should be altered to include or exclude cyclic irrigation, scheduled cycle skips to allow for dry down, syringing cycles to cool foliage, etc. During phase 1 of this project, growers and researchers constantly provided feedback on hardware (Kantor 2012), and more importantly software (Kantor and Kohanbash, 2012) bugs and successes, in order to create a graphical user interface (GUI) that best served the grower and allowed for customization based on grower needs. Overall, both grower cooperators were extremely pleased with the monitoring ability of the WSNs. More importantly, utilization of WSNs to monitor soil moisture levels caused substantial and nursery-wide changes in irrigation behavior that improved plant health without negatively affecting profitability (due to increased production costs) or production cycles (by lengthening cycles) (Majsztrik et al., 2012).

Phase 2, initiated in 2011-12, maintained the same software and hardware from phase 1 (with only slight upgrades) while incorporating the ability of the WSNs to monitor and *control* irrigation (Lea-Cox and Belyaneh, 2012). Irrigation control is achieved by setting a minimum soil moisture level in the software/GUI. When soil moisture drops below the set point, the software will initiate a predetermined irrigation cycle, defined by the grower in the software GUI (Kantor and Kohanbash, 2012). Irrigation control, unlike monitoring, has required retrofitting of existing irrigation systems to ensure solenoid control is linked to WSNs and not standard timers. In doing so, several hardware issues have been identified and remedied, particularly residual voltage that can cause solenoid malfunctions. Despite these challenges, as in phase 1 of this project, utilization of WSNs to monitor soil moisture levels has caused substantial and nursery-wide changes in irrigation behavior that has improved plant health without negatively affecting profitability (due to increased production costs) or production cycles (by lengthening cycles). In fact, cropping cycles have been reduced, disease incidence and severity have been reduced, fertilizer use has been reduced and plant growth regulator use has been reduced as a result of monitoring *and* controlling irrigation by using WSNs (Majsztrik et al., 2012).

The story of system deployment and implementation at these two nurseries will be presented as a case study broken into phase 1 and phase 2 of deployment and implementation.

McCorkle Nurseries

Four WSNs were installed in a 1-acre production area to monitor substrate water content in various gardenia crops in 2010. However, due to our desire to study comparative water use between a monitored system and a monitored and controlled system, control capability was quickly initiated. To control irrigation we used MoistureClick irrigation controllers (Dynamax, Houston, TX) (Fig. 1).

Figure 1. A MoistureClick irrigation controller with soil moisture sensor.

We compared water use of plants irrigated with these controllers to water use in plots irrigated by McCorkle's irrigation manager. Most of the crops were inside a large greenhouse (Fig. 2), with one crop grown outdoors on a gravel pad.

Figure 2. An overview of the study with gardenia 'Heaven Scent' at McCorkle Nursery.

The most interesting results from our work at McCorkle Nurseries, Inc. in 2010-11 came from a study with gardenia ‘Heaven Scent’, a problem crop for this and many other nurseries. This cultivar is very susceptible to a variety of pathogens and growers typically lose about 30% of the crop to water molds (root pathogens). By monitoring and controlling irrigation using soil moisture sensors, we hoped to minimize overwatering and reduce disease. Surprisingly, we found that water use was similar. Unbeknown to us, McCorkle’s adjusted the irrigation in their plots to match the volume of water that was applied in plots controlled by MoistureClick controllers, as determined by flow meters that tracked irrigation volumes of the two treatments.

Although this study appeared to be a total loss from a comparison perspective, we noticed that disease was not a problem in this crop. Additionally, plants grew much faster than normal and the production time was decreased dramatically (6-9 months) (Fig. 3). By reducing diseases and shortening the production cycle, there was an economic benefit of roughly $1/ft2. This does not take into account the reduced need for fungicide applications or the opportunity cost related to the ability to start growing another crop in this same space (this was greenhouse space, which is highly valued). Clearly, the payback time for wireless networks is very short if such financial returns can be obtained!

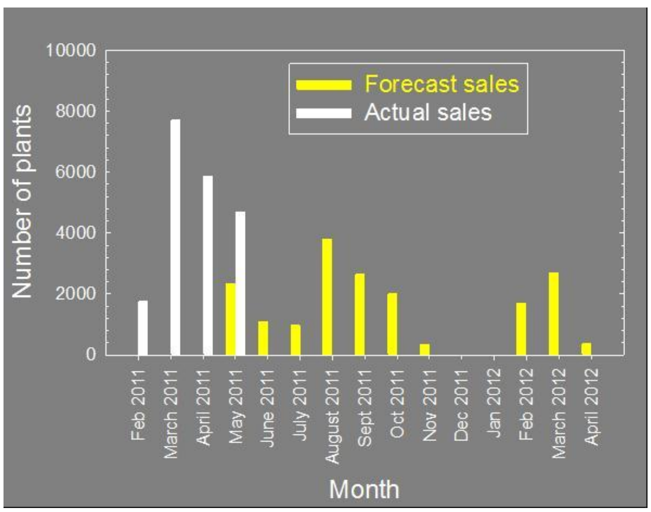

Figure 3. Forecast and projected sales of gardenia 'Heaven Scent'. Note that better control of irrigation resulted in much improved growth and quicker sales. The sorter production cycle reduced production costs.

In 2011-12, the wireless sensor network at McCorkle Nurseries has been upgraded to Decagon nR5 nodes with fully automated irrigation control in two nursery locations; one 2-acre covered house and another 4-acre production house. Also, unlike the previous system, the updated monitoring and control system was wired directly into the existing McCorkle’s control timer. During this process, some hardware issues in the Decagon nR5 nodes were identified. Examples include; the relay in nodes was not sized to facilitate control of more than 3-4 solenoid valves with a single node and there was an issue with AC current ‘leakage’ in the 24 VAC detection circuit. After many trials and errors, the system became fully functional in late April, and we have been controlling irrigation in a 2 acre greenhouse since then. We initially used 8 Decagon nR5 nodes to operate the 54 valves in the 2 acre greenhouse. Each valve controls water flow to multiple overhead, stationary sprinkler heads. We have since scaled this back to 7 Decagon nR5 nodes, based on the crops that are currently grown in this greenhouse. Having such a large number of valves in the greenhouse created significant challenges in setting up the network, but now that it is in place, also provides McCorkle Nurseries with much flexibility in how they can configure the system. They can easily change what valves are controlled by what node, and are thus able to reconfigure the irrigation setup based on their production needs.

Initial results of the irrigation control at this nursery have been stunning: the first crop that was grown completely using the sensor network was a gardenia ‘Heaven Scent’ crop that was placed in the greenhouse on June 18, 2012, with an anticipated finish data of July 2013 (Fig. 4). Growth rate of the plants was much faster than anticipated and some of the plants were ready for sale in September 2012, and all plants will be finished this fall. McCorkle Nurseries may not sell all plants this fall, but that is due to market limitations, and not the salability of plants themselves.

Figure 4: The first gardenia crop irrigated entirely using the wireless sensor network. Note that the anticipated finish date on the label on the right was May 2013. Plants were all ready for sale in fall 2012.

Following the very positive results seen in this 2-acre greenhouse, we have now installed Decagon nR5 nodes (with Decagon EC-5 sensors) in a 2^{nd}, 4-acre greenhouse. The configuration of the irrigation system in very different from that in the greenhouse were we installed the first part of the network: the 2^{nd} greenhouse has only two valves, each controlling approximately two acres of irrigation using overhead impact sprinklers. This greenhouse is currently used for hydrangea production.

Evergreen Nursery

Initial setup of the WSN at Evergreen nursery was initiated in 2010, with the goal of monitoring irrigation practices. The wireless sensor network at Evergreen consisted of four Decagon EM50R loggers that transmitted data to a Base Station at the nursery office. One of the Decagon EM50R loggers functioned as a weather station with a temperature and humidity sensor, light (PPF) sensor and rain gauge. The other three loggers were used to monitor substrate water content in several different crops (e.g. gaillardia, Heuchera, and ferns). Will Ross, the grower at Evergreen, monitored the system and utilized the information to help him make daily irrigation decisions. From looking at the data, Will noticed that some of his crops (e.g. gaillardia) were drying out faster than he realized. To reduce drought stress and improve plant growth, he changed irrigation practices for his gaillardia crop from once a day to twice a day; with smaller irrigation volumes at each irrigation event. This allowed him to better meet the water demands of the crop while minimizing leaching. The computer screenshot below (Fig. 5) shows that Will changed the manner that he irrigated this crop on October 14, 2010. The pink bars show irrigation events, and while he initially irrigated once a day, you can see that he switched to watering twice a day while reducing the amount of water applied at each irrigation event.

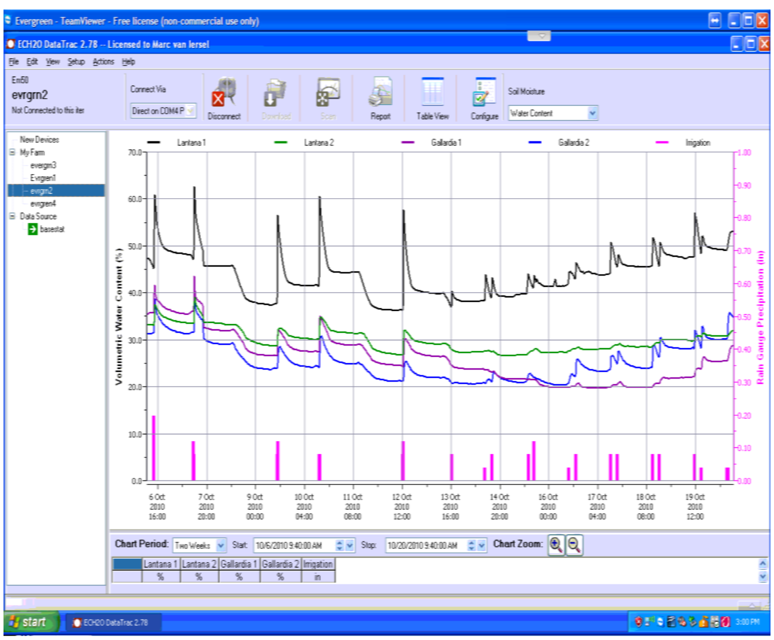

Figure 5. A screenshot for the computer at Evergreen displaying substrate water content measurements (lines) and irrigation (pink bars). Note the switch to irrigation twice daily during the latter part of this period.

Will Ross also focused on trying to reducing leaching. We have worked together on interpreting the data, and have looked specifically at the rate of decrease in substrate water content following irrigation. Since Evergreen uses small containers, we felt confident that a rapid decline in substrate water content following irrigation is indicative of leaching (rather than the water draining to part of the substrate below the sensor). We introduced Will Ross to the ‘Delta VWC’ tool that has been incorporated into SensorWeb at our request. Delta VWC shows the change in substrate water content since the previous measurement and is ideally suited for monitoring leaching. This is but one example of how grower input has resulted in improvements of software and/or hardware products being developed as part of this project.

In 2012, the WSN at Evergreen was upgraded, with the addition of several Decagon nR5 nodes over the summer of 2012. Will Ross, the grower at Evergreen (Fig. 6) had been using WSN data to help him make better irrigation decisions (including switching from once daily to twice daily cyclic irrigation to reduce leaching in 2011).

Figure 6. Will Ross, grower at Evergreen, in a cold frame at the nursery. Note the wireless node above his head, and the rain gauge among the plants used to monitor irrigation. Four pots have sensors to measure substrate water content.

The current network configuration consists of three Decagon EM50 and five Decagon nR5 nodes (Fig. 7). All nodes are using Decagon EC-5 sensors and the Decagon nR5 nodes have been configured for irrigation control. The nR5 nodes are controlling irrigation in five hoop houses and two small greenhouse sections (one of which currently is uncovered). Crops grown in these sections include heucheras, euphorbs, echinacea, lavender, and hellebores. The automated irrigation was started in early August and it is still too early to determine if it has any clear effects on crop health or production cycle speed. However, the system has worked well and all crops appear to be doing well.

Figure 7. An nR5 node used as part of our wireless sensor network. Up to five sensors can be plugged into the ports at the bottom. On the right side there is a relay that can be used to open and close irrigation valves (red and white wire). The nodes transmit all collected data to a base station and computer using a radio signal.

Conclusions

These two case studies exemplify the enormous strides that can be taken in product development, deployment and implementation when researchers work hand-in-hand with commercial growers. This research project has resulted in successful WSN implementation at two commercial nurseries in Georgia that now trust and rely on WSN data to mot only monitor substrate moisture but to also control substrate moisture via 100% automated irrigation control. Not mentioned in this article, but of vital importance, is that similar grower implementation of WSNs, related to this project, is occurring in Maryland, Colorado, Tennessee and other states. When asked if growers would invest in a commercial product, the response is a unanimous yes. When asked why, growers point to reductions cropping cycles, disease incidence and severity, fertilizer use and plant growth regulator use; all as a result of monitoring *and* controlling irrigation by using WSNs.

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Irrigation Scheduling Software Development

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Abstract. *Current developments in the next generation Wireless Sensor Networks (WSN's) allows for distributed irrigation control from a centralized basestation. This work presents several methods of irrigation control based on WSN's as well as the user interface to make it happen. WSN irrigation methods start with manual commands, moves onto node based irrigation, and then extends to a global based irrigation approach. The user interface needs to be able to configure the different modes while allowing users to monitor irrigation spatially as well as temporally. This work explores the tradeoffs in node software development to allow for optimal node performance. One of these innovations is a configurable pulse time for irrigation events. This system is deployed and being tested in different types of agricultural environments to help determine irrigation scheduling needs of various agricultural techniques. Developing new irrigation software that allows for clear and easy control is critical as new systems are fielded to improve the user experience and provide the requisite details to irrigate ideally.*

Keywords. WSN, wireless sensor networks, irrigation, control, intelligent, user interface, GUI, software, base station, basestation

Introduction

Irrigation control is a critical task in any growing operation. Wireless Sensor Network's (WSN's) can be used for increased irrigation precision while also reducing the work load of the irrigation manager [Majsztrik, Lichtenberg & Lea-Cox, 2012]. In this work a commercially available WSN system from Decagon Devices, Inc. is further developed to control irrigation solenoids and a new user interface [Kohanbash et. Al. 2012a] was developed to allow for easy and flexible data access, to help make sensor data actionable, and to allow irrigation to be managed from a centralized location.

Irrigation Control

WSN's provide a unique platform for irrigation control. By nature a WSN system has many inexpensive nodes that are distributed in many locations. This is beneficial since agricultural sites may contain several hundred different crop species [Lea-Cox & Belayneh, 2012]. In many cases, including in this work, WSN systems also have a central basestation that is responsible for collecting all of the data from the nodes. These attributes make WSN systems ideally suited for irrigation control. A central basestation that is remotely accessible by the growers can be used to configure and monitor irrigation while each node is located near the irrigation zone that it is controlling. This interaction between a distributed control system and a centralized interface allows for advanced irrigation methods to be developed.

Hardware

The WSN node was developed by Decagon Devices, Inc. (Pullman, WA), based on its existing Em50R node. The Em50R was chosen as a base due to its reliability, ease of use, and wide array of compatible sensors [van Iersel, 2012]. Two new nodes (Fig. 1) were developed the nR5 and the nR5-DC. Both nodes are capable of reading from up to 5 sensors and have an onboard relay that can be used for controlling solenoids. The nR5 is capable of controlling 24VAC solenoids. After testing and fielding the nR5, growers wanted a node that was easier to deploy. A new node the nR5-DC node was developed which uses onboard power to control 12V latching solenoids, this advance allows growers to not run power to each irrigation site to control the solenoid, saving both time and money. The nR5-DC makes this system highly portable and allows growers to modify irrigation zones on the fly.

Fig 1. Inside of an nR5-DC node used for irrigation control. Solenoid wires can be seen to the right of the batteries [Lea-Cox & Belayneh, 2012].

Irrigation Modes

There are four primary modes of irrigation available [Kohanbash et al. 2012b]. The first is a manual mode that allows growers to specify and "override" irrigation settings to manually command an irrigation event to occur. The second type is schedule based control. This approach is similar to existing schedule based controllers. The third type is local set-point control. This mode allows each node to control irrigation based on a specific soil moisture value using attached or "local" sensors. In all of the previous modes the settings are configured on the basestation and sent to the node where the node can then decide whether irrigation should occur, while the basestation is used to send the settings to the node it is not required after that as the node controls all irrigation functions. The final mode is called global control; this mode uses the basestation to actively control irrigation. Global control lets nodes control irrigation based on data from other nodes as well as from grower tools that are user configured. Grower tools take on the form of simple tools such as dew point, averages, vapor pressure deficit (VPD), and growing degree days (GDD) as well as more advanced tools [Kohanbash et. al. 2011] based on plant physiology [Bauerle et. al., 2006; Starry et. al., 2011; van Iersel et. al., 2010; Kim, 2012]. Some of these advanced growing tools allow plant models to use environmental conditions as inputs to determine if irrigation should occur.

Pulse Types

Another innovation is pulse types. Within each irrigation event, as defined by the four modes above, the user can control exactly how irrigation water is applied. For example a user can specify that an irrigation event should turn on for 60 seconds, turn off for 30 seconds, and then repeat that cycle 5 times for every event commanded (Fig. 2). This allows for micro-pulse irrigation [Lea-Cox & Belayneh, 2012; Kohanbash, et al. 2012] and other benefits such as allowing water pressure to build between irrigation applications and allowing the sensors time to measure soil moisture between events.

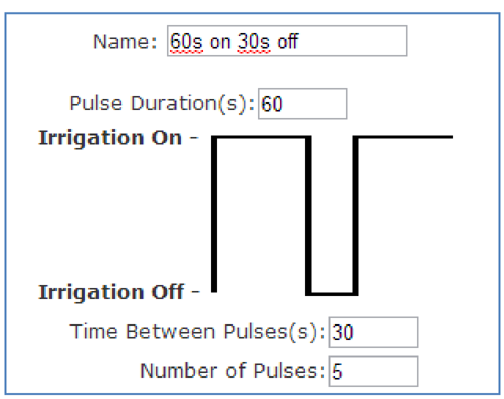

Fig 2. Segment from the user interface that lets users graphically define pulse types.

Irrigation Monitoring

Irrigation control is important but knowing when and how much irrigation occurred is also critical [Majsztrik, Lichtenberg & Lea-Cox, 2012]. Within the sensorweb system there are multiple ways to view irrigation. The home page that provides a spatial view of the site can also show irrigation quantities by color coding the nodes (Fig. 3), the data view page shows not only the amount of irrigation used but the moisture value that the node is using for controlling irrigation. There is also a charting tool that lets irrigation events be plotted with other data (Fig 4). The previous methods for viewing irrigation requires a user to go to the basestation's interface and look at the data, this system also features alerts that can send an email or text message to users. The alert is user configurable and can be based on too much irrigation being applied, to little irrigation being applied, or a daily alert that specifies how much irrigation occurred. Alerts can also be used for sensor data and not just for irrigation values.

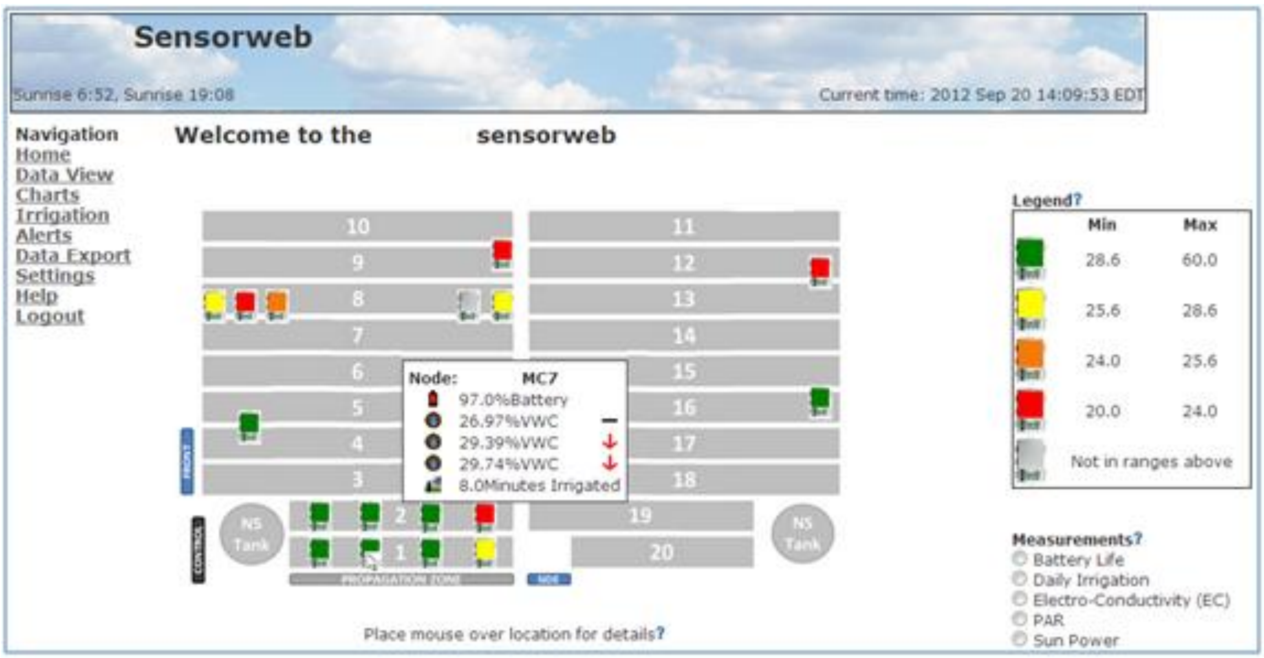

Fig 3. Spatial view showing data and color coded nodes. Irrigation can be seen in the pop-up box.

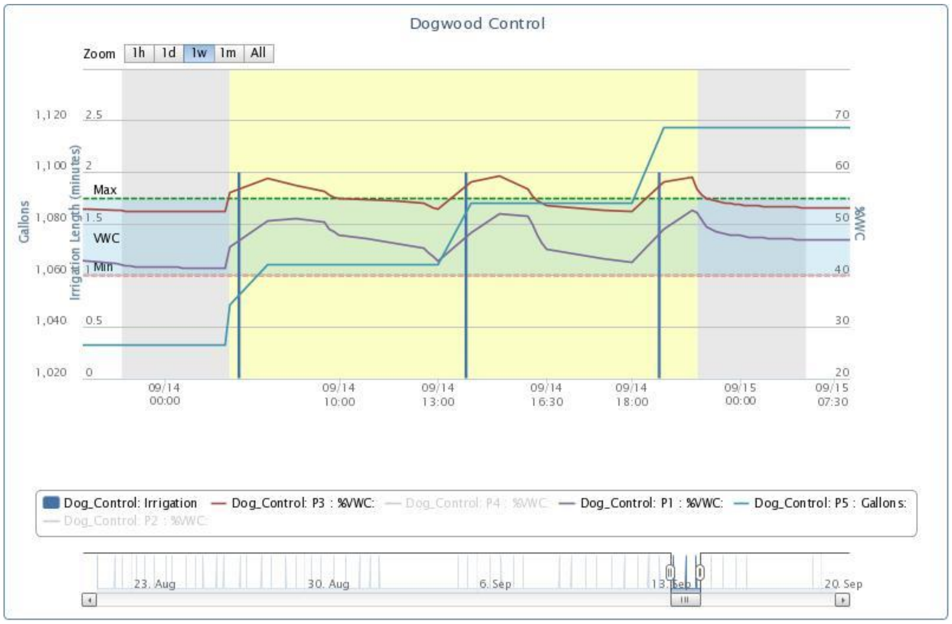

Fig 4. Chart showing blue vertical bars for irrigation and horizontal lines with soil moisture sensors (see Lea-Cox & Belayneh, 2012 for more information). The horizontal blue band is a user defined region for optimal moisture levels.

For configuring irrigation parameters an easy to use interface [Kohanbash et. al., 2012] was created as well as assistive tools such as showing all of the irrigation schedules on a single page and showing how many nodes are irrigating at a given time (Fig. 5).

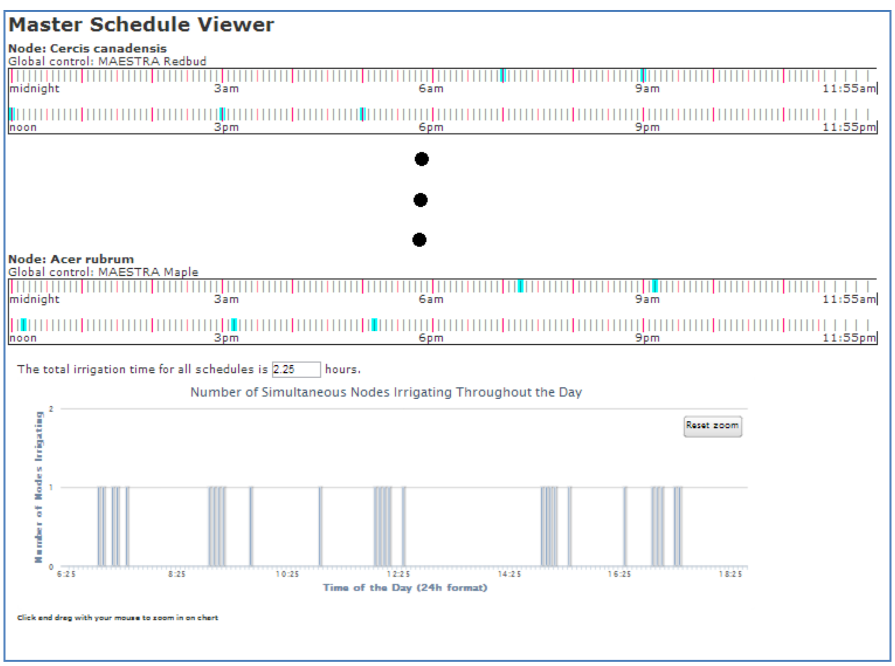

Fig 5. Image showing multiple schedules on one page for comparison and also a plot that shows all irrigation overlaid on each other.

Error Detection

Error detection is another critical aspect that must be mentioned. The internal software on the node is able to detect many sensor faults. This is primarily done by comparing sensor values to the known range of valid sensor readings. The node is also able to send error messages to the basestation that are then displayed for the user. In the user interface bad sensor values are shown in red so that they are more noticeable to the user. While a lot of work has been put into error detection there are still certain errors that cannot be detected at this point. For example if a sensor gets pulled out half way and is still returning a value within its valid range the system cannot detect it.

Conclusions

Wireless sensor networks are a versatile tool for irrigation managers [Lea-Cox, 2012]. This system has been deployed at over a dozen sites throughout the county and has been used at various sites including greenhouses, nurseries, and orchards. The WSN model for irrigation allows direct integration of plant science models that allows the benefit and value of WSN based irrigation systems to be increased [Chappell & van Iersel, 2012]. Ongoing field work is being conducted that is quantifying the benefits of WSN based irrigation control (please visit http://smart-farms.net for more information).

Acknowledgments

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Next-Generation Monitoring and Control Hardware Development

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Abstract. *Wireless Sensor Network (WSNs) systems form an invaluable tool in agriculture. Currently these systems are good at reporting and logging data. This work extends WSN's for the next generation of systems. The next generation needs to have a nimble user interface capable of viewing and analyzing the data in real time. To extend the WSN capability the next step is adding direct irrigation control from the WSN nodes.*

This work focuses on the development of a WSN system that gives users the ability to get actionable results from the data, as well as monitor and control irrigation from a central location. A node capable of controlling irrigation was developed as well as a secure protocol to safely communicate between the basestation and the node. Other issues such as system security, graphical tools, and data management are discussed. This system is deployed at over a dozen sites and is constantly evolving based on user feedback.

Keywords. WSN, wireless sensor networks, irrigation, control, intelligent, hardware, nodes

Introduction

Wireless Sensor Network's (WSN's) for agriculture are becoming more popular as the systems become more mature and can provide financial benefit [Chappell & van Iersel, 2012; Majsztrik, Lichtenberg & Lea-Cox, 2012]. These systems provide real-time data that is important for making critical irrigation decisions [Lea-Cox. et. al. 2009]. Making every aspect of the WSN work reliably is important for wide scale adoption. This work presents some of the design decisions for this system as well as the WSN system that was produced. The node was developed by Decagon Devices Inc. and the user interface and basestation was developed at Carnegie Mellon University.

Wireless Measurement and Control Node

Within a WSN system the node is the device that collects data from the sensors and transmits the data to the basestation (discussed in the section below).

Hardware

Two nodes (Fig. 1) were developed for this project by Decagon Devices Inc. For reliability purposes the design was based on the existing Decagon Em50R node. The first node developed with irrigation control capability was the nR5. The nR5 is capable of switching a 24VAC solenoid valve that is standard in many irrigation applications. Based on feedback from growers, Decagon also produced the nR5-DC node that is capable of controlling DC latching solenoids. These new latching solenoid valves do not require external 24VAC power to operate; this decreases the expense and labor of setting up an irrigation block while also making the irrigation blocks more flexible. The nR5-DC uses the internal power supply to generate the positive and negative voltage necessary to switch the DC latching solenoids. Both nodes maintain the Em50R nodes ability to read up to 5 sensors [van Iersel, 2012]. The nodes also have an integrated circuit to detect if the voltage is correct for irrigation to occur. This provides a good first order alert to growers that an error exists in their irrigation system.

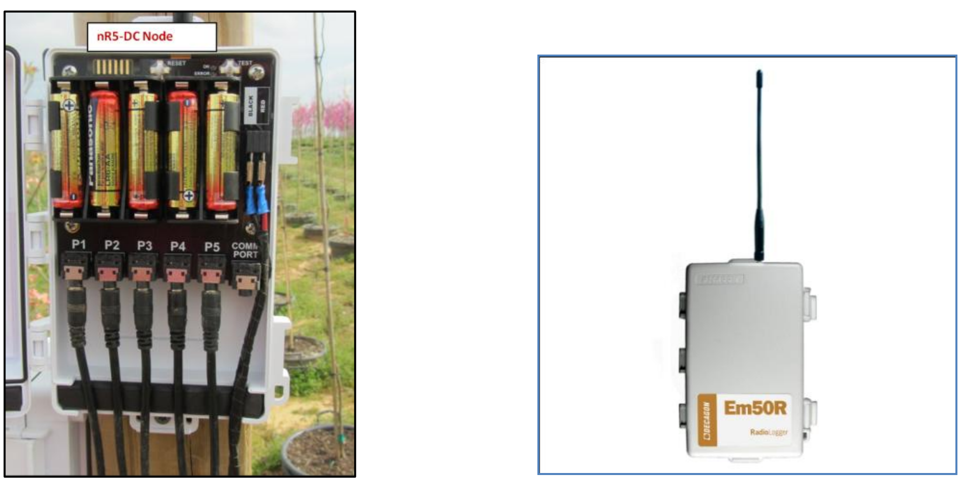

Fig 1. Left: Inside of an nR5-DC node used for irrigation control. Solenoid wires can be seen to the right of the batteries [Lea-Cox & Belayneh, 2012]. Right: External image of a node [Decagon, 2012].

The nodes use a 900MHz ISM radio which allows for better penetration through crops and for an increased range compared to higher frequency radios such as the popular 2.4GHz ISM bands. There are also user configurable channels so that multiple WSN systems can be used in close proximity without interfering with each other.

Node Firmware

The node software is responsible for reading data from the sensors, controlling irrigation, and transmitting the measurement and status data to the basestation. The nodes use a binary protocol that was developed for this project. Using a binary based protocol allows more data to be transmitted per packet as opposed to an ASCII based protocol. The data packet size is optimized for efficient transmission based on the radio being used in the node. Minimizing data transmissions helps increase the battery life in the node. This protocol allows for two way data transmission so that users can adjust settings from the basestation and do not need to physically go to the node.

To insure integrity of the transmitted data the node uses cyclic redundancy check (CRC) codes in every packet. The basestation software then uses the same algorithm to check that the packet is valid by re-computing the CRC and comparing it to the transmitted CRC code. The system employs a confirmed delivery protocol to verify that the basestation received the data. After every data transmission the node listens for a confirmation from the base that includes the packets CRC and a sequence id. The node will repeat this up to 10 times in an attempt to transmit the data to the basestation. The node and basestation software use this single confirmation step when transferring measurement and status data and when responding to simple commands. For manual irrigation commands, a double confirmation approach is used to prevent accidental over-irrigation. When a manual irrigation command is sent from the basestation to the node a special confirmation packet is sent back to the basestation, in response the basestation confirms that it received the special confirmation packet.

Every 24 hours the node also transmits all of its configuration and status information to the basestation to give the system user the ability to monitor the health of the wireless network. In small embedded systems keeping track of accurate time is often a problem. In this system every time the base sends a confirmation packet to the nodes it has the current time in the packet that the nodes can then use to correct its internal clock.

In order to save battery power, the node powers down the radio immediately after it receives a confirmation packet from the basestation software. If the basestation needs to send additional data to the node, it sets a flag in the confirmation packet to instruct the node to stay awake for a short interval and listen for incoming packets.

Controlling irrigation with sensor measurement is not a trivial task. This system was designed with error detection and safe failure modes designed to protect a growing crop. Before any irrigation event occurs that is based on a sensor measurement, the node verifies that the sensor value is within a pre-defined range of valid values. If the average of several sensors are used for control decisions, only sensors reporting valid values are used in the average. This type of system catches many of the observed sensor problems; however, there is opportunity for improvements in this area. For example if a soil moisture sensor is only partially inserted into the ground it might return a valid value for a working sensor and trigger an irrigation event that is not desired since the moisture measurement would be low.

The nodes report general irrigation status and error messages to the basestation during each scheduled irrigation event. Examples of reported messages can be as simple as what it is using as a time source to status about why an irrigation event failed.

Basestation

Hardware

The basestation in this system is an inexpensive netbook (laptop) computer and a radio module. A netbook was chosen since it allowed for easier debugging in earlier systems. While the original plan was to switch to an embedded computer with no display once the system had matured, users liked having the netbook as part of the system. Most of the systems are operated remotely over the internet however when users are on site and want to quickly check something the netbook with its integrated screen is useful. Also many agricultural sites are in remote locations and internet can be unreliable, by using the netbook a user can get direct access to the system.

The basestation radio connects to the netbook over USB. The radio module consists of the antenna, the radio and a weather resistant enclosure. The communications channel in the radio can be changed to match the channel of the nodes radio in order to successfully communicate with different networks.

Fig 2. Basestation radio module

Basestation Software

The basestation computer uses an SQLite3 database for storing all of the node sensor data as well as for all node settings. SQLite3 was chosen since it is file based and has fast query times. SQLite3 is slower than some other database types for inserts; however, there are relatively few inserts and this database needs to have fast queries for when it is pulling lots of sensor data for tasks such as generating charts. Since these queries can be very large it is important to carefully construct queries so that only the necessary data is selected.

The user interface [Kohanbash et. al. 2012b] is written in Ruby on Rails. This is a web based interface that can be accessed over the internet and is tied in directly to the database. The user interface is password protected to prevent unauthorized users from entering the system. Also within this system there are various access levels ranging from only being able to view data, to being able to control irrigation, to full administrator access.

The user interface (Fig. 3) is designed to let users view data at a glance while also giving the ability to delve into the data for further analysis. This interface is a central location where users can also configure node settings (Fig. 4) and irrigation parameters. This saves the user from having to go to each node and manually make changes. The interface is also able to issue alerts so that growers can be made aware of conditions based on sensor data or irrigation as they occur with emails or text message notification.

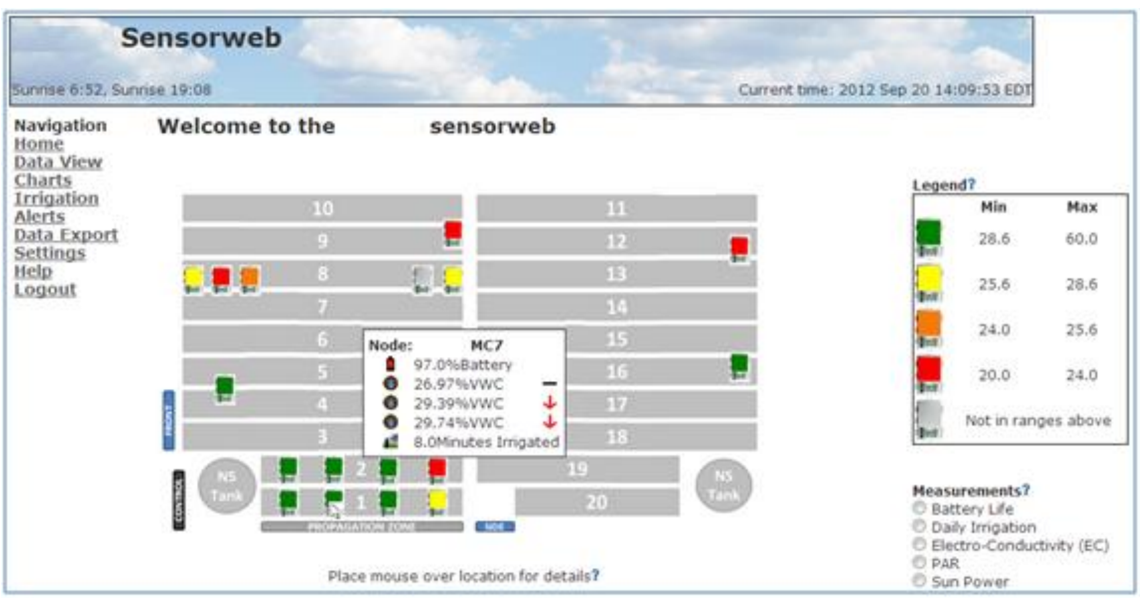

Fig 3. Spatial view showing data and color coded nodes.

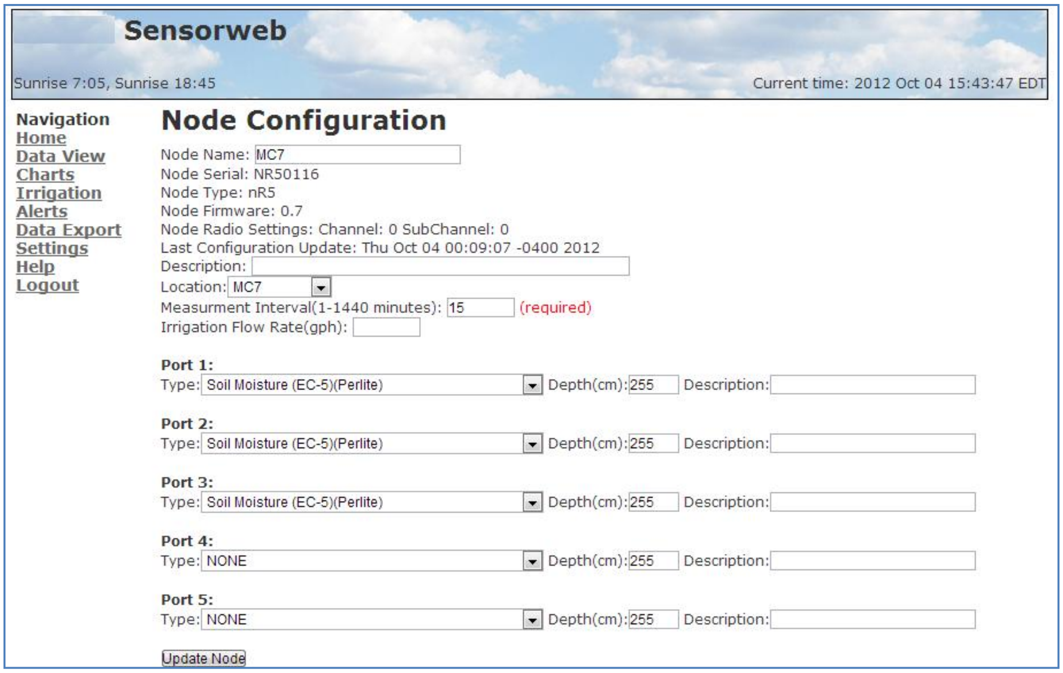

Fig 4. User interface page for configuring node settings. Irrigation parameters are configured on a separate irrigation page.

Node Reliability & Deployments

This system has been running at over a dozen agricultural sites (Fig. 5) over the past few years with new sites continuing to be added [Chappell & van Iersel, 2012]. The system can be setup out of the box without engineering support and runs continuously without the need of constant system rebooting. The nodes have a long battery life that minimizes direct user to node contact.

Fig 5. Map showing location of Sensorweb sites (Image of the USA is from Wikipedia).

Conclusions

Wireless Sensor Networks are proving themselves to be valuable within agricultural environments [Kohanbash et. al. 2012b]. By creating reliable systems with features such as irrigation control and the ability to have an actionable outputs [Kim, 2012] these systems continue to grow. This work demonstrates a system that is easy to setup, easy to use, and reliable. This system is actively being used by growers and researchers in a variety of environments including green houses, nurseries, green roofs, and orchards.

Acknowledgments

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A National Perspective on Irrigation Trends and Sensor Network adoption in Ornamental Nursery and Greenhouse Operations

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Keywords: survey, wireless sensor network, ornamental, greenhouse, container, field

Abstract

The way that irrigation water is applied within ornamental operations is dependent on a number of factors including the type of operation, the amount and quality of water available, and the irrigation infrastructure present within each operation. Wireless sensor networks can provide additional information which growers can use to monitor soil moisture and the microclimate in an operation, to determine how to irrigate more efficiently. The results presented here are a part of a larger project aimed at developing the hardware and software required to implement irrigation monitoring and control networks in intensive horticultural operations. As part of this project, we have developed and implemented an extensive survey, to understand current national perceptions, trends and practices for irrigation and water management in ornamental operations. Surveys were distributed through regional and national grower organizations and state ornamental extension agents, as well as through trade shows. The general perception of using sensor networks was found to be positive, with many respondents indicating that they thought these systems would benefit them at their operation. In regards to irrigation practices, growers were found to rely heavily on qualitative methods, such as visual appearance, crop development, or time-based scheduling, compared with quantitative assessment methods, such as leaching fraction. An integration of environmental conditions and plant response was often used for adjusting irrigation schedules in greenhouse and container operations.

Introduction

How irrigation water is applied and how irrigation scheduling decisions are made have major impacts on plant growth, yield and quality. In ornamental operations, supplemental irrigation is typically required for greenhouse and container operations. Irrigation is often applied in field operations for establishing transplants and maintaining adequate soil moisture during drought. Irrigation managers base their irrigation decisions on a number of factors including crop type and maturity, container size, previous and future weather conditions, and type of irrigation system used (Majsztrik et al., 2011). The goal of an irrigation event is usually to provide the plant with enough water to replace the amount loss due to evapotranspiration, while avoiding nutrient leaching losses due to over irrigation. Current irrigation application is often applied in excess of plant water requirements to ensure adequate soil moisture (Lea-Cox, 2012). Applying irrigation more efficiently has the potential to reduce labor and water pumping costs, maintenance costs for equipment, reduce disease pressure and subsequent agrochemical application costs, and reduce crop production time. Until recently, it has been difficult to obtain real-time, accurate soil/substrate moisture levels. A national specialty crops research project is currently underway to correlate the impact of a better understanding of soil moisture and irrigation decisions on ornamental plant production using wireless sensor networks (Lea-Cox et al., 2010). For more information about this project, and our results to date, see additional articles by contributing authors in these proceedings (Chappell and van Iersel, 2012; Kantor et al., 2012; Kim, 2012; Kohanbash and Kantor, 2012; Lea-Cox and Belayneh, 2012; van Iersel, 2012), or visit the project website at www.smart-farms.net.

Materials and Methods

An extensive survey was developed and targeted at greenhouse, container and field operations growing ornamental plants for wholesale or retail sale in the United States. Growers were contacted in two main ways, through emails and by direct contact at trade shows. For email contacts, ornamental nursery and greenhouse extension specialists were contacted in each state. The extension specialists were asked if they would be willing to help distribute emails through their listservs, and asked to contact state nursery and landscape and greenhouse organizations to help facilitate survey dispersal via their listserves. A state-level approach was used for several reasons. These listservs were likely to be the most comprehensive and up-to-date contact lists, and growers were thought to be more receptive to a survey being distributed through their state contacts. Also, there would be no breach of confidentiality, since we did not have direct access to email addresses. All extension specialists and grower organizations that were willing to participate were compiled into a database. Emails were sent to state contacts, who then forwarded the information on to their listserves. Survey responses are still being collected through the end of 2012, but preliminary results based on collected responses are presented here.

Growers were also asked to participate in the survey at tradeshows. Tradeshows were used to contact growers that might not be on listserves, and allowed for interaction with individual growers. Five tradeshows were visited across the United States (Maryland, Alabama, Ohio, California, and Oregon). Growers were asked about their operation to determine if they produced ornamental plants for wholesale or retail markets. If so, they were asked to fill out this anonymous survey, and were given business cards with information about the survey, and the web site for survey completion. All growers were given the option to "opt-in" by providing contact information at the end of the survey, for follow up purposes, but this decision was entirely voluntary.

Results and Discussion

We do not know the total number of potential respondents that were reached through email and tradeshows, but there are approximaltely 39,000 operations in the US (Alan Hodges, Extension Scientist, Univ. of Florida, Pers. Comm.). Surveying by email led to a relatively high response rate, since individuals who received the email, but did not click to start the survey were not counted. A total of 132 responses have been collected to date, with 104 (79%) respondents indicating that they were willing to participate and met the criteria for participation (they worked at an ornamental operation). A total of 52 respondents (39%) completed the survey. Results provided below are based on the number of responses for each question, with a varying number of responses throughout the survey. The number of respondents and completed surveys is lower than expected, and grower participation will continue to be requested in the upcoming months. A large grand prize incentive was recently added, and it is hoped that it will increase response rates.

In order to determine where revenue was received, growers were asked about the revenue contributed by each type of operation. Container operations were reported to contribute an average of 44% of total revenue, greenhouses contributed 31%, field operations accounted for 23% of income, and other farming operations accounted for an additional 2% of income.

A. Sensor Networks

Part of this survey assessed how likely growers would be to use irrigation sensor networks to provide real-time information at their operations, and the perceived benefits and drawbacks of these networks by grower / managers. When asked whether they would use a sensor network at their operation, 46% said they would be likely to use one, while 54% were unlikely to use a sensor network at this time. Considering that there was limited information in the survey about what a sensor network was capable of, and the benefits that were seen across a variety of growing situations, this was considered a relatively high positive response response rate. It is not likely that 46% of growers would use sensor technology, since this is a hypothetical situation, but the growers seemed to understand the potential applications of these kinds of systems to their operation.

Growers were asked what way they thought sensor networks would benefit their operation. Respondents believed sensors would increase irrigation efficiency (87%), increase plant quality (82%), reduce product loss (71%), reduce disease occurrence (69%), help manage growth rates (67%), reduce management costs (60%), and reduce monitoring and time costs (49%). Survey respondents saw the potential for sensor networks to benefit their operations, and had high expectations that these networks would help to produce better plants. It was not clear why growers had such a positive view of this type of irrigation technology. Based on results collected to date, sensor networks have been implicated in providing some of these benefits under a variety of conditions and production environments. Those same growers were concerned that sensors would be too expensive (77%), not reliable (52%), would not control irrigation correctly (45%), and would have too many maintenance requirements (29%). The major respondent concerns centered around cost and proper functioning, which are not trivial.

It is clear that the growers in this project, growing in a variety of locations and a variety of species and types of operations, see the benefit of these networks, and place a high value on the information that they provide. Sensor networks have been shown to reduce irrigation requirements in ornamental plant production (van Iersel et al., 2009; Chappell et al., 2012). However, initial cost and maintenance considerations may still be important considerations, depending upon the net benefit (return on investement) that sensor networks can provide(van Iersel et al., 2009; Chappell et al., 2012).

Saving irrigation-related (resource-use) expenses through the use of sensor networks will likely add a modest increase to the net profitablity of ornamental operations. In small operations, irrigation-related expenses accounted for 6.4% of their overall costs, 10.0% for medium size operations and 2.3% for large operations (Table 1; sum of water treatment, pumping costs, water purchases, labor for irrigation system and cost of irrigation maintenance). The cost of buying, pumping, and treating water and maintaining the irrigation system turn out to be a relatively small portion of an operation’s expenses, although the percentage of cost appears to be higher in mid-sized operations compared to larger operations.

The real benefits of these sensor networks are derived from a combination of reduced irrigation costs, which can be significant in some situations, coupled with additional saving that can be realized through better control of irrigation. For example, deployment of a sensor network in a Gardenia (*Gardenia augusta* ‘Heaven Scent’™) crop cut both production time and disease losses roughly in half; combined with savings in expenditures on fertilizer and fungicide use, these improvements in productivity more than doubled annual profit (Chappell et al., 2012). These experimental results, combined with the survey data on the relative importance of cost items associated with sensor use, suggest that the greatest financial benefits from sensors are likely to come from improvements in disease management, fertility management, and accelerated growth rather than from savings in irrigation alone.

Table 1. Weighted average percent cost by operation size, from a national survey of ornamental growers. Note that data is not segemented by operation type (e.g. field, container-nursery or greenhouse operation).

Gross annual income ($)	**0-200,000**	**200,000-1,000,000**	**1,000,000 +**
Fertilizer	2.66%	2.34%	2.02%
Disease management	0.98%	0.86%	2.60%
Water treatment	0.00%	0.24%	0.10%
Pumping costs	2.04%	1.48%	0.65%
Water Purchases	0.66%	0.45%	0.43%
Labor for irrigation system	1.52%	5.42%	0.81%
Cost of irrigation Maintenance	2.22%	2.38%	0.30%

B. Irrigation applications

Respondents were asked whether they monitored irrigation water (quality and / or quantity) at their operation. In general, monitoring rates were highest in greenhouse operations, which is not surprising since irrigation water quality has a major impact on plants, especially young plants. Irrigation water coming out of nozzles was monitored by 48% of greenhouse, 42% of container, and 32% of field growers. Container and field growers were more likely to monitor containment ponds (29% and 27% respectively) compared to greenhouse growers (16%).

The type of irrigation system has direct impacts on distribution uniformity, labor, and the volume of water required to irrigate a crop. Greenhouse operations most often used hand irrigation (32%), overhead (31%), drip (18%), and boom sprinklers (9%). Container-nursery operations most often used overhead irrigation (49%), drip irrigation (33%), or hand irrigation (18%). Field operations reported mainly using drip irrigation (56%), while 19% used overhead, and 18% used traveling guns.

Determining evapotranspiration, and therefore when and how much irrigation to apply is a decision that incorporates a number of environmental (i.e. temperature, humidity, wind speed) and plant-based factors (i.e. growth phase, container size, substrate water holding capacity) (Bacci et al., 2008). Growers were asked about the qualitative methods that they use to help schedule irrigation. Greenhouse growers most often (95%) use visual observations (apprearance, weight etc.), crop development (80%), time-based delivery which may or may not be adjusted for season or plant species (55%), and much less often an indicator plant species (17%). Container operations reported using visual observations (100%), crop development (80%), time-based (64%), and indicator species (24%). Field operations typically use visual observation (88%), indicator species (81%), crop development (69%), and time-based methods (50%), to determine when to schedule irrigation events. Visual observation was most often cited as the qualitative criteria used to determine whether irrigation should be applied.

Growers were also asked about quantitative methods that were used at their operations. Environmental conditions were most often cited as used to help schedule irrigations (85% greenhouse; 80% container and 56% field). Soil moisture sensors were reported to be used for 17%, 8% and 6% for greenhouse, container and field operations respectively. Measuring leaching fraction was reported for 20% of container-nursery operations and 6% of greenhouse operations. It is not surprising that leaching fractions were measured infrequently, considering the labor costs involved; however, it is a relatively quick and efficient way to measure how much of applied irrigation is leaching through a container, allowing for adustment of irrigation durations.

Conclusions

Although survey responses are still being collected, these preliminary data suggest that growers believe that sensor networks have the potential to increase the efficiency of their operation, although there are percieved operation and maintenance issues. Irrigation decisions require the integration of a number of variables to determine when and how much irrigation should be applied. It appears that growers most often use qualitative, and to a lesser degree quantitative information to make irrigation decisions, which speaks to the overall cost structure of most ornamental operations, as resource costs are relatively low compared to labor and other costs. Understanding the true cost of over-irrigation (in terms of crop health and other cost issues) is likely an under-recognized factor in irrigation scheduling among ornamental producers. Recognition of the cost of reduced productivity due to inefficient water management is likely to increase demand for sensors and other forms of information provision that allow growers to improve irrigation management.

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Integrating Soil Moisture and Other Sensors for Precision Irrigation

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Abstract. The use of sensors can provide quantitative information to help guide and automate the decision making process for irrigation. This paper provides an overview of the most common sensors that can be used for this purpose. Such sensors include those that are commonly used for weather stations as well as sensors that indicate the water needs of the crop. Irrigation demand can be determined directly from soil water measurements or indirectly from the water status of the crop. Pros and cons of these approaches are discussed.

Keywords. Evapotranspiration, Light, modeling, relative humidity, remote sensing, temperature, water, wind

Introduction

Sensing environmental conditions is becoming easier and cheaper, providing opportunities to integrate such sensors into irrigation systems. Good, quantitative information can be used to help guide decision making with regard to a) when to irrigate and b) how much water to apply. However, simply collecting data may not be useful, unless that data is presented in an actionable form; the data need to be converted into usable information. Thus, the software side is at least as important as the hardware. This paper focuses on available sensors for use in irrigation control systems, while other papers from this workshop discuss the hardware needed to measure and collect the data, software development to present the data in a user-friendly, actionable format, the use of sensor networks for irrigation management, and the economic impact wireless sensor networks can have.

There are different ways in which sensor data can be used to help make irrigation decisions. The simplest method is to turn irrigation on and of based on whether a particular sensor reading is below or above a particular threshold. For example, irrigation can be turned on and off based on the amount of water present in the soil or based a measure that is an indicator of plants stress. More complex approaches may involve the modeling of crop water use or evapotranspiration (ET, the total amount of water evaporating from the soil and transpired by the crop) based on weather conditions and crop factors.

Although there are many different ways to estimate ET from weather conditions, the most common approach is the FAO Penman-Monteith method, which uses commonly measured weather data to calculate a reference ET value (ET_0). The ET_0 is an estimate of the ET from an extensive surface of green grass with a height of 12 cm (about 5"). This ET_0 is than multiplied by a crop coefficient (K_c) to calculate the expected ET for a particular crop. Crop coefficients depend on the size of the crop, and thus change over time. Detailed information on K_c values is available for most agronomic crops and some horticultural crops. This approach is difficult to apply to landscapes with mixed plantings, because of the difficulty of determining an accurate K_c. Note that the resulting ET estimates assumes that the crop has access to unlimited water resources, and adjustments need to be made if water availability is limited by drought or salinity. Weather information needed for the FAO Penman-Monteith method include solar radiation, temperature, relative humidity, wind, and rain. The 'simplified' equation to estimate ET using the FAO Penman Monteith method is:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Why is this rather complicated equation considered a simplification? Because using this equation, we can estimate ET_o from just a few readily available measurements: temperature, radiation, wind speed, and relative humidity. This makes it possible to calculate ET_0 from standard weather station data. The units for ET_o are in mm/day, or can be converted to inches. For more details, see Allen et al (1998).

There is no general agreement whether it is better to control irrigation directly using sensor readings or based on model predictions of ET; different applications may require different solutions. ET modeling generally works well for large scale, agronomic crops or turf grass, but is more difficult to apply in landscapes with a large variety of plants or in situations where accurate K_c values may not be available. Another option is the combined use of sensors and models, where irrigation could be controlled using models, while sensors are used to assure the plants do receive adequate water (or vice versa).

Sensing Weather Conditions

Weather conditions play a large role in determining water use, and thus irrigation requirements, of crops. In many cases, weather data are available from nearby weather stations, in which case an on-site weather station may not be necessary. However, when using weather data from an off-site weather station, it is important to verify that the information from that station is actually applicable to the site of interest. Micro-climatic differences are common, and as a result, there can be significant differences in weather conditions among sites that are close together. The one weather variable that is perhaps most different across relatively small distances is rainfall.

Light

Light, or solar radiation, is probably the most environmental variable affecting plant water use. There are two common ways to measure light that are relevant to plants a) the total energy of the incoming light (shortwave radiation) and b) photosynthetically active radiation. The difference between these two measures is that shortwave radiation includes near UV, visible, and near infra-red radiation, spanning radiation of wavelengths from approximately 200 to 3000 nm. These wavelengths span the entire spectrum of radiation coming from the sun and shortwave radiation measurements thus determine the total energy flux of the incoming sun light (in units of W/m^2). Photosynthetically active radiation only includes light with wavelengths from 400 to 700 nm, roughly the same wavelengths visible to the human eye. Light within this part of the spectrum can be used by plants to drive photosynthesis and is measured in units of $\mu mol/m^2/s$. Thus, measuring shortwave radiation treats light as an electromagnetic wave and determines the energy in that radiation, while photosynthetically active radiation treats light as individual light particles (photons) and determines the number of photons in the incoming radiation.

Photosynthetically active radiation is normally measured using quantum sensors. Since these sensors measure the light that plants can use for photosynthesis, quantum sensors are often used when the collected data are needed for plant growth models. Such models can be coupled to water use models as well, in which case quantum sensors can be used for irrigation management. However, weather stations typically do not include quantum sensors. Photosynthetically active radiation data are used in both very simple (van Iersel et al, 2010) and complex water use models (Bauerle and Bowden, 2011)

Measuring shortwave radiation is critical in determining the energy balance of a leaf or crop. Energy balance calculations are used in the FAO Penman-Monteith model of ET and shortwave radiation measurements are thus critical for weather stations, if the weather data are to be used for ET modeling. Sensors that measure total solar radiation are referred to as pyranometers and normally part of weather stations, so these data are readily available.

Light intensities also are commonly measured with photometric sensors (although not as part of weather stations), in units of lux, lumens, or footcandles. Photometric sensors measure how well humans can detect the light. Since the sensitivity of the human eye is very different from the way plants perceive light, these measures should not be used for irrigation control purposes.

The calibration of light sensors drifts gradually over time, and often in an unpredictable way. To assure long term reliability, sensors need to be recalibrated ever 2-3 years (see manufacturers info for more details). Recalibration requires a standard light source and generally needs to be done by the manufacturer.

Temperature and relative humidity

Although very different, temperature and relative humidity are discussed together, because their effects on plant water are interdependent. Specifically, relative humidity itself does not have a direct impact on (evapo)transpiration. Instead evapotranspiration depends greatly on the vapor pressure deficit, which is a function of both temperature and relative humidity. To better understand this relationship, a clear understanding of some key terms is needed.

- Vapor pressure (e) is a measure of the actual amount of water vapor in the air. Vapor pressure is expressed in pressure units (kPa, mbar).
- Saturation vapor pressure (e_S) is a measure of the maximum amount of water vapor the air can hold. This is a function of temperature, with warmer air being able to hold more water. Saturation vapor pressure is expressed in pressure units (kPa, mbar).
- Vapor pressure deficit (VPD) is the difference between the maximum amount of water the air can hold and the actual amount of water vapor in the air ($e_s - e$).
- Relative humidity (RH) is the ratio between the actual amount of water vapor in the air and the maximum amount of water vapor the air can hold. It is most commonly expressed as a % ($e/e_s \times 100$).
- Dew point temperature is the temperature to which the air must be cooled to completely saturate the air with water vapor (*i.e.* reach 100% RH). When the dew point is reached, dew (condensation) will form if the temperature drops further.
- Dry bulb temperature is the actual temperature of the air
- Wet bulb temperature is the temperature of a thermometer covered with a wet wick and exposed to air flow. Evaporation of water from the wick will cool the thermometer, and the wet bulb temperature is thus always lower than the air temperature, but higher than the dew point(unless RH = 100% in which case wet bulb temperature, dry bulb temperature, and dew point are the same).

The driving force for evapotranspiration is VPD, but unfortunately, we cannot measure VPD directly. Weather stations normally determine VPD from the dry bulb temperature and relative humidity. For applications that require great accuracy, dry bulb and dew point can be measured and used to calculate VPD, but accurate dew point measurements are too expensive and technically challenging for use in irrigation management.

Typically, weather stations include a temperature sensor and relative humidity sensor. There are many different types of temperature sensors,, but weather stations most commonly use either resistance temperature detectors (RTD) or thermistors. Both sensor types are based on the same principle: the electrical resistance of the RTD element changes with temperature and the resistance of the element is measured. This measured resistance is then used to determine the temperature. Although temperature measurements seem simple, larger errors can occur if the sensor is not used properly. Most importantly, sensors should always be shaded and preferably aspirated.

Relative humidity is normally measured using capacitive sensors. These sensors contain a substrate between two electrodes and the amount of water the substrate absorbs depends on the relative humidity. The two electrodes are then used to measure the capacitance (for more details, see the section on capacitance soil moisture sensors) of the substrate and the resulting measurement is converted to a relative humidity value. The calibration of humidity sensors normally drifts gradually over time and these sensors should be recalibrated every 2-3 years to assure that the readings are accuracy.

Automated weather stations can then calculate the saturation vapor pressure, actual vapor pressure, and vapor pressure deficit from the temperature and humidity values.

Wind

Wind affects evapotranspiration, because air movement moves the humid air away from the canopy or soil and reduces the boundary layer resistance for water movement from the soil or crop to the air. Wind direction is generally less critical for irrigation management, but is measured by many common weather stations as well.

The most common method to measure wind speed is with cup anemometers. The wind causes the cups to rotate around a vertical shaft and the number of rotations within a particular time interval is measured to determine the wind speed. Thus type of anemometer is normally present on weather stations.

Another type of anemometer on weather stations is the windmill type, where a propeller is spun by the wind and the rotations of the propeller are measured. To assure that the propeller is perpendicular to the wind, a wind vane is normally used to align the instrument to the prevailing wind direction.

Hot wire anemometers are used more in research applications and consist of wire with an electrical current going through it. This current changes the temperature and thus the electrical resistance of the wire. Wind will cool the wire and the actual temperature and resistance of the wire are thus dependent on the wind speed. The resistance of the wire can be measured using several different approaches, but the basic operating principle of all hot wire anemometers is the same.

Wind direction. Although generally not critical for irrigation applications, wind direction is normally measured by weather stations, using a vane. This vane can rotate and its angle depends on the prevailing wind direction. At very low wind speed, the wind may not have enough force to push the vane around, and wind direction measurements can become inaccurate.

Rain

Rainfall is obviously critical in irrigation applications and is generally measured using a tipping bucket rain gauge. Rainfall is collected into a funnel and the water is directed towards a spoon-like device. When enough water collects in this spoon, it will tip, causing an electrical signal to be sent (using a reed switch). Weather station rain gauges typically have a resolution of 0.2 mm or 0.01”. Rainfall can also be measured using simple rain gauges, which vary greatly in their design. Simple rain gauges do not allow for automated data collection and are therefore not used as part of weather stations.

For irrigation purposes, it is not always necessary to know how much rain has fallen. Some irrigation systems simply have a rain sensor that can turn off irrigation when it is raining, without measuring how much rain is actually falling

Ideally rain gauges would not just determine the daily amount of rainfall, but also the intensity of the rainfall. Rainfall intensity in many situations will help determine how much water will infiltrate the soil and how much water is likely to be lost as surface runoff. Although most automated weather stations are capable of measuring this, they are often not configured to do so. This is an area where it would be easy to make progress towards making weather data more usable.

Soil vs. Plant Sensing

Irrigation decisions can be made by measuring the water status of the soil or crop and there is no agreement about which of these approaches is better. Proponents of measuring crop water status argue that the goal of irrigation is to assure adequate water availability to the crop and that crop water status is therefore the best indicator of whether irrigation is needed. However, crop water status is generally more difficult and expensive to measure than soil water content. In addition, crop water status is not only affected by the availability of water in the soil, but also by short term changes in weather (such as a clouds passing over) and by diseases and pests (particular those that affect the root system and thus the water uptake of the crop).

Soil water measurements have the advantage that they are relatively easy to make and automate. In addition, using soil water status to make irrigation decisions results in a simple feedback system: a low soil water content will trigger irrigation, which increases soil water content and indicates that irrigation is no longer needed.

Both crop and soil water status measurements need to take into account spatial variability. Soils are often not homogenous, resulting in spatial differences in soil water content. Whenever possible, such spatial variability should be quantified and the placement of sensors should take into account this spatial variability. In many cases this means that at least some sensors should be placed in the driest part of the field to assure that this part of the field receives adequate water.

Crops, likewise, are not homogenous. Spatial variability in the crop can result from natural variability among the plants, spatial variability of the soil, fertilizer placement, or environmental gradients within the field. In addition, there are distinct diurnal patterns in crop water status that make these data difficult to interpret. If individual plants are monitored to make irrigation decisions, larger plants may need to be monitored to assure that those plants receive adequate water. Remote sensing applications can alleviate issues related to spatial variability to some extent, either by measuring many plants and reporting an average or by mapping the spatial variability. For an excellent review on the implications of spatial and temporal variation on irrigation management, see the reviews by Jones (2004, 2007).

In many cases, the largest reason for spatial variability may actually be the design of the irrigation system itself: if the uniformity of the irrigation system is not good, spatial variability in soil water content and plant growth will be the inevitable result. Thus, any approach to precision irrigation needs to start with proper design, installation, and maintenance of the irrigation system. However, those topics go beyond the scope of this paper and are discussed in many other irrigation association papers.

Sensing Soil Water

Water content vs. matric potential

Two basic properties of soil (or in the case of greenhouse and nursery production, soilless substrates) can be measured, soil water potential and soil matric potential. There is no agreement which measure is better suited for irrigation management (see Jones, 2007).

Soil water content sensors, as the name implies, measure the amount of water in the soil, while matric potential sensors measure how easy it is for plants to extract water from the soil. Matric potential and soil water content are related to each other, but this relationship is different for different soils and can be determined from soil moisture retention curves, which show the relationship between substrate water content and matric potential (Fig. 1).

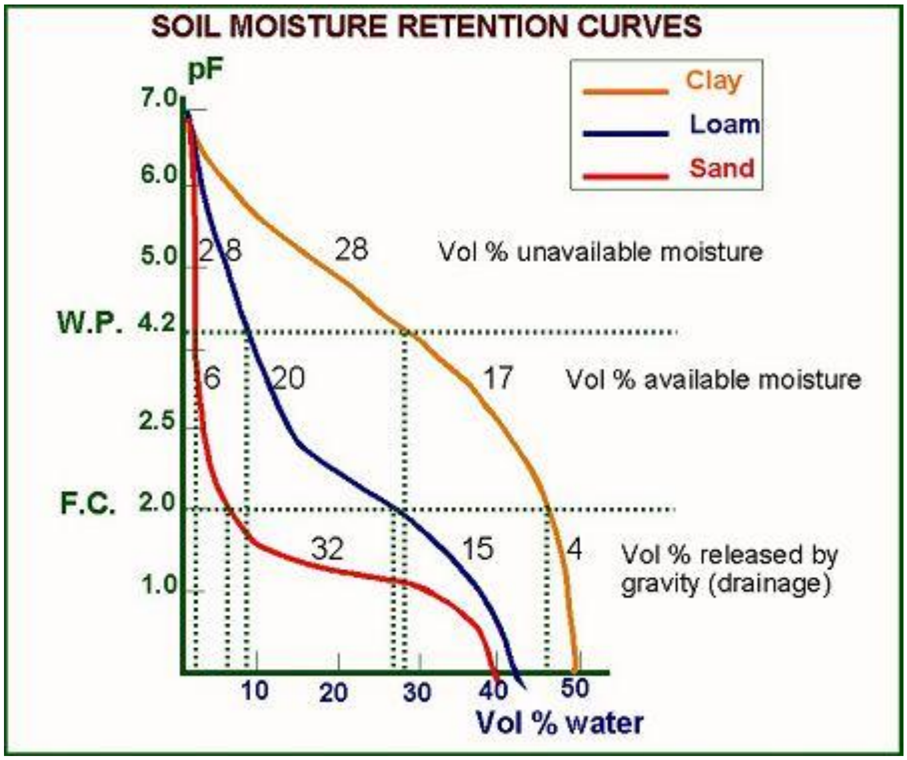

Figure 1. Typical soil moisture retention curves for thee different soil types. Soil matric potential is expressed on a logarithmic scale (y-axis, pF). W.P. is the permanent wilting point and F.C. is field capacity.

Thus, soil water content measurements indicate how much water is present, but not whether this water is actually available to the crop. This is critical in understanding the limitations of soil water content sensors: a soil water content of, for example, 20% provides absolutely no usable information about whether the water is plant available and whether or not irrigation is needed. In soils with a high clay content, a 20% water content likely means that there is little or no plant available water in the soil: the water is bound too tightly to the soil particles and plants cannot easily access that water. In that case irrigation is needed. In a sandy soil, on the other hand, 20% may be near field capacity and the soil water is readily available to the plants. Irrigation likely would simply result in draining of water below the root zone. To be able to interpret soil water content measurements, a basic understanding of soil properties is absolutely essential. When this information is available, soil water content measurements make it very easy to use those data for irrigation management, because it becomes very easy to calculate how much water needs to be applied when the irrigation is turned on. And if the flow rate of the irrigation system is known, it is simple to determine for how long to run the irrigation.

Soil matric potential has the advantage that it directly determines whether the soil water is available to the plants. Once an appropriate threshold for a particular plant/crop has been determined, this threshold can be used in different situations, regardless of soil type. However, matric potential data provide no information on how much water should be applied. To determine this, an understanding of the soil properties is required.

Water content sensing

The most accurate method to measure soil water content is with the use of a neutron probe. Neutron probes contain the radioactive element Beryllium. Beryllium emits 'fast' neutrons and when these neutrons collide with water molecules, they slow down and some of them will bounce back to a detector inside the probe. These slow neutrons are measured and used to determine the soil water content. Unfortunately, neutron probes are expensive and require special handling due to the emitted radiation. Use of neutron probes has thus been largely limited to research.

More common probes take advantage of the high dielectric of water. The dielectric refers to the interaction of water molecules and an electromagnetic wave or field that is applied to the soil. Most soil materials have a dielectric of about 4, air has a dielectric of 1, and water has a dielectric of about 80. Thus, changes in soil water content have a drastic effect on the total dielectric of the moist soil. Different sensors detect these changes in the dielectric of the soil and the dielectric values then are converted to soil water content. Among sensor types that use the dielectric properties of soils are time-domain reflectivity (TDR) sensors, time domain transmisometry (TDT), and capacitance sensors. TDR has long been the standard method of measuring the dielectric properties of soil; the sensors themselves are cheap, but an expensive meter is needed to measure the sensors. In the last decade, other approaches have been developed to use the dielectric properties of soils (TDT, capacitance). These newer sensors do not require an expensive meter and have facilitated the incorporation of soil moisture sensors into irrigation control systems.

Despite the claims from some manufacturers, all sensors that rely on the dielectric properties of soils benefit from a soil specific calibration. There are large enough differences in the dielectric properties of different types of soils to affect the measured dielectric of the soil. This becomes especially critical if such sensors are used in soils with high organic matter content, high salinity, or in soilless, highly porous substrates used in horticulture (*e.g.* Crespo and van Iersel, 2011).

Matric potential sensing
Matric potential of the soil is most commonly measured using tensiometers. Tensiometers measure soil matric potential (suction) directly, and the data do not depend on soil type or texture. No soil specific calibration is needed. Tensiometers do require routine maintenance, because they contain water which needs to be replenished on a regular basis. Tensiometers only measure matric potential within a fairly limited (wet) range, but this is generally adequate for irrigation in horticultural or agronomic applications.

A different approach to sensing matric potential is the use of gypsum blocks or Watermark sensors. These sensors have a matrix that can absorb and desorb water in response to changes in soil matric potential. The electric resistance of this matrix changes as the amount of water in the matrix changes, and the electrical resistance is measured and then converted to a soil matric potential. Gypsum blocks have the disadvantage that they gradually dissolve over time, which led to the development of the Watermark sensor, which does not have this problem. Because the electrical resistance of the matrix does not only depend on water content but also on dissolved ions, these sensors tend to be sensitive to changes in soil electrical conductivity, and thus fertility and salinity.

More recently, hybrid sensors have been developed that apply the principle of dielectric sensors to determine matric potential. A dielectric sensor is embedded with a ceramic material (matrix) and the matric potential of this ceramic material equilibrates with the matric potential of the surrounding soil. The dielectric sensor is then used to measure the dielectric of the ceramic material and this value is then converted to a soil matric potential.

Soil Salinity
Salinity measurements are important in irrigation methods, because irrigation not only serves to apply water to a crop, but also plays a critical role in the prevention of salt build up in the soil. Salinity levels in soils are generally determined from the ability of a soil to conduct electricity (electrical conductivity or EC), which can be expressed in dS/m or mS/cm (those units are equivalent).

The most accurate methods of determining soil salinity are lab-based tests, where soil samples are collected and sent off to an analytical lab for analysis. It is important to note that different labs may use different methods to measure salt concentrations in the soil, and that results from different labs may thus not be comparable. The most common methods are the saturated soil extracted and 1:2 and 1:5 dilution technique. Dilution techniques results in lower values than the SSE method when equal amounts of soils are present.

Soil EC can also be determined from the dielectric properties of soils, which makes it possible for techniques like TDR to measure both soil water content and EC simultaneously (Dalton and van Genuchten, 1986). Likewise, the EC of soils can be measured using electrodes inserted in the soil and measuring the conductance (the inverse of resistance) of the soil. One drawback to both of these methods is that they measure a property referred to as the bulk soil EC, or the ability of the combination of soil particles, air spaces, and the soil solution to conduct electricity. This property has little practical value, since it is difficult to convert that value to either the total amount of salts present in the soil (which is critical for salinity management) or the EC of the soil solution (which determines the physiological responses of plants to salinity. Although models have been proposed for converting bulk soil EC to solution EC (e.g. Hilhorst, 2000), there are questions about the accuracy of the various methods. Advances in our ability to measure soil EC could have great benefits for our ability to manage both salinity and fertilizer applications.

Sensing Plants

Many different approaches to sensing plant water status have been used, and this is just a selection of the many methods available. The goal of sensing plant water status is to determine whether the plant is under stress and thus needs water. This also goes to one fundamental weakness of any plant-based sensing method: by the time a stress can be detected, productivity likely has been lost already. That may not matter in most landscape situations, but in horticultural and agronomic applications, where maximizing yield is an important goal, plant-based methods may result in yield losses.

Sap flow

Different methods for measuring the flow of xylem sap through plants have been used and tried for irrigation control. The most common methods are the heat balance method (where a small part of stem is heated and the heat balance of the stem is calculated) and the heat pulse method (where needles inserted in the stem are heated and the heat dissipation is measured). These methods can give accurate information about sap flow through the plants, but the data can be difficult to use for automated irrigation management. Sap flow not only depends on the availability of water in the soil, but also on the weather conditions, and health of the plants. Thus, a decrease in sap flow may not indicate the need for irrigation, but could simple be due to clouds passing over. This makes automation based on these data difficult, but the results still provide valuable insights into the water dynamics of the crop.

Leaf temperature

A simple method to get an indication of the level of drought stress a crop is exposed to is to use of leaf or canopy temperature data and to determine how this differs from air temperature.

Measuring leaf (or canopy) and air temperature can be used to calculate a crop water stress index (CWSI). Irrigation decisions are based on canopy foliage and air temperature under given meteorological conditions in comparison with canopy foliage temperature of a well-watered crop. This approach requires an infrared thermometer - a hand-held or remotely mounted device that can measure canopy temperature. This approach is based on the principle that transpiration cools the canopy and a well-watered canopy, therefore typically has a temperature lower than the air temperature, while a drought stressed canopy typically will have a higher temperature than the air.
The CWSI is calculated as:

$$CWSI = \frac{(Tf - Ta) - (Tf^{*} - Ta)}{(Tf - Ta)_{max} - (Tf^{*} - Ta)}$$, where

$Tf - Ta$ = Foliage-air temperature difference of crop in question

$Tf^{*} - Ta$ = Foliage-air temperature difference of well-watered crop under same environmental conditions.

$(Tf - Ta)_{max}$ = Foliage-air temperature difference when crop is maximally stressed (transpiration = 0) under same environmental conditions.

The CWSI is therefore a unitless number between 0 and 1, giving a “relative” indication of stress level. A value of 0 indicates that the crop is not water stressed at all, while a value of 1 indicates the maximum stress level.

Leaf wetness

Leaf wetness sensors determine are designed to mimic leaves and measure when and for how long the leaves are wet. This is particularly important for the prevention of a variety of foliar diseases, since certain pathogens require liquid water on the leaf surfaces to complete their life cycle. Leaf wetness can thus be used to help determine how different irrigation schedules may impact disease development. Two types of leaf wetness sensors are commonly used: a) sensors that measure the electrical resistance along the outer surface of the sensor. These sensors normally have two electrodes that form a grid throughout the sensor and the resistance between those two sensors is measured. When the sensor is wet, the water will conduct electricity and the resistance drops. The other type of leaf wetness sensor takes advantage of the dielectric properties of water and is essentially a modified soil moisture sensor. Rather than measuring soil water, these sensors simply measure the presence of water on the surface of the sensor. Both types of leaf wetness sensor are sensitive to dirt accumulation and should be kept clean.

Remote sensing

The crop water status can be determined using spectral reflectance measurements. When light hits a leaf, there are three possible fates for any particular photon (light particle): it can be absorbed by the leaf (pigments), reflected, or transmitted. Light reflectance can change dramatically when plants are exposed to drought stress, especially in the near infra-red part of the spectrum (just above 700 nm and not visible to the human eye). By measuring the reflectance of light of different wavelengths [normally red (R) and near infra-red (NIR)], a ratio can be calculated that indicates the stress level of the plant or crop. Among the ratios being used are:

- The normalized difference vegetation index or NDVI = (NIR-R)/(NIR +R)
- The ratio vegetation index or RVI = NIR/R

Neither index is a direct indicator of drought stress; other factors, and especially how much of the plant canopy covers the soil, affect these indexes as well. Thus, these indexes do not have some magical threshold below which the crop needs water; instead it is important to look at changes in the values of these indexes over time.

Many other methods of remote sensing have been used for irrigation control. For a more comprehensive overview of remote sensing techniques, see Bastiaanssen (1998).

Sensing the Irrigation System

Sensors are not only useful to determine when and how much to irrigate, but also play an important role in checking the performance of the irrigation system and can be used to detect maintenance problems. The two most useful things to measure are flow rate and water pressure.

Flow meters

Flow meters should be part of any commercial irrigation systems. Not only do they provide a record of water use, they also can be used for trouble shooting purposes, such as leak detection. There are many flow meters available that can easily be incorporated into larger sensor networks. The most common flow meters have a paddle wheel that rotates faster as the flow rate increases, but many other technologies are available as well.

Water pressure

Measuring the water pressure in the irrigation system is valuable for leak detection (since leaks can reduce water pressure), but also to assure that there is adequate pressure for proper operation of the irrigation system. A lack of pressure is especially common in large irrigation systems that use multiple valves. If too many irrigation valves open at once, water pressure may be too low for the irrigation system to irrigate properly.

Conclusions

Sensing environmental and other conditions can provide information that can be used to greatly increase the efficiency of irrigation systems. It is important to realize that sensors can be used to collect large amounts of data, but these data have little value with efficient ways to collect, store and process them. First of all, for large scale sensing, appropriate hardware is needed. An example of the development of the hardware needed for wireless sensor networks is described by Kantor et al (2012). Along with this hardware a software interface (or graphical user interface is needed to present the data has in such a way that it is converted into usable, actionable information (see Kohanbash and Kantor, 2012). Our group has successfully used newly developed hardware and software for on-farm irrigation scheduling (Chappell and van Iersel, 2012, Lea-Cox and Belyaneh, 2012). Irrigation can be based on soil/substrate water content measurement or on models that predict crop water use (e.g., Kim, 2012). A survey of the greenhouse and nursery industry has shown that there is widespread interest in the use of sensor networks for irrigation monitoring and control (Majsztrik et al, 2012) and this may help move the industry from irrigation practices that rely heavily on qualitative indicators of crop water needs to more quantitative methods. We have already seen that such a switch to more quantitative irrigation methods can help save large amounts of water (van Iersel, et al, 2009) and increase growers profits (Chappell et al, 2012).

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Water Savings of ET vs. Timed Water Applications

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Purpose

This paper discusses the results of 2 years of a 3 year irrigation scheduling study commenced in August 2010 in central Florida outside of the Orlando area on turf grass (St. Augustine 'Floratam'). The purpose of this study is to compare and measure the water conservation capabilities of two different types of irrigation system controls. One is a conventional timer based control, operating on a set duration and frequency; the other is a weather driven, evaporation/transpiration derived control that utilizes a computer based algorithm to determine the frequency and duration of the irrigation cycle.

Methodology

The test area consisted of twelve 15 x 15 foot plots all irrigated with spray sprinklers on a 15 foot x 15 foot spacing on each corner. The plots where individually metered and controlled from a Rain ESP-LX field satellite, controlled by a Rain Bird MaxiCom central control system.. The ET calculation was provided by a Campbell Scientific weather station located approximately 30 feet from the plots installed on the same turf grass. The plots consisted of 4 control plots, 4 weather based plots and 4 time based plots (Figure 1). Water use was tracked monthly. Weather, including rainfall, ET and run times were tracked daily. Effective rainfall was considered to the first 0.5 inches of any given storm. Additionally, the plots where evaluated for turf quality each month based on the University of Florida protocol.

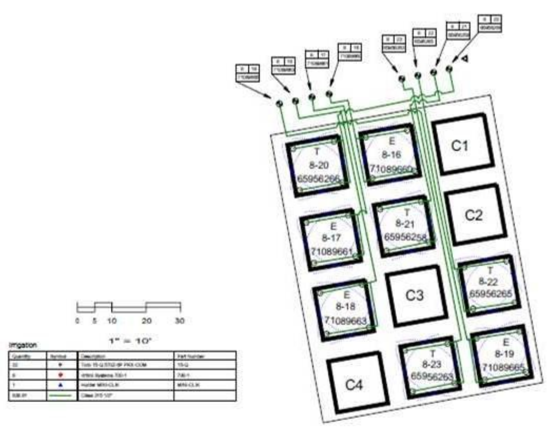

Figure 1. Plot Layout

The time based plots were irrigated with 0.75 -1 inches of reclaimed water per week only on Tuesdays and Thursdays as per the existing statute in effect from the South Florida Water Management district. The ET based plots were irrigated based on the ET reading from the weather station with a Landscape Coefficient of 0.8 and watered on an as needed basis with no restriction as to how many days per week. The control plots were watered for establishment and received only direct rainfall and are maintained in the same frequency and with the same strategy as the irrigated test plots. Irrigation for all plots is typically between midnight and 7:00 am.

Toro 570Z-6PRXCOM spray sprinklers with 15Q Toro Precision nozzles in each irrigated plot provide the irrigation. This sprinkler has pressure regulation, check valve and a high flow shut off device that automatically reduces flow if a nozzle is removed or damaged. Each of the 12 plots is controlled by a dedicated Irritrol 700-01 valve with a 40 psi inline pressure regulator. Upstream of each electric valve is a 5/8 inch water meter to quantify water usage.

In August 2010 an irrigation audit was conducted to measure the uniformity and precipitation rate of each plot. While it is standard practice to link similar sized areas with similar irrigation, eight individual audits were conducted, one for each plot. The auditing method was identical for each plot following the Irrigation Association's auditing guidelines. After catchment placement each zone was operated for exactly 10 minutes and the volume of each catchment recorded. There was no wind measured at the adjacent weather station anemometer during the course of the eight audit catchment tests. The results of each test were analyzed to calculate DULQ, DULH, and Run Time Multiplier (RTM). The results are shown in Table 1.

Table 1: Auditing Results

Valve #	**Irrigation Type**	**DU_{LQ}**	**DU_{LH}**	**RTM**	**Precipitation Rate**
8-16	ET	64.2 %	82.3%	1.28	0.93 inches/hr
8-17	ET	73.7%	85.5%	1.18	0.91 inches/hr
8-18	ET	64.4%	80.8%	1.28	0.88 inches/hr
8-19	ET	48.5%	72%	1.45	0.82 inches/hr
8-20	2x/week	64.8%	82.2 %	1.27	0.85 inches/hr
8-21	2x/week	55.5%	80.4%	1.36	0.88 inches/hr
8-22	2x/week	67.1%	83.9%	1.25	0.88 inches/hr
8-23	2x/week	61.4%	81.2%	1.31	0.85 inches/hr
Average ET	ET	70.6%	85.4%	1.22	0.87 inches/hr
Average 2x/week	2x/week	65.5%	84.6%	1.26	0.86 inches/hr
Average	All	69.7%	85.4%	1.22	0.87 inches/hr

The variation in DU_{LQ} is difficult to explain. In almost all cases two of the four corner catchments were extremely low volumes. If the cause was because of the catchment being too close to the sprinklers one would expect all four corners to be consistently low. Additionally, in most cases, the corner catchments on the east side of the plots were the lowest readings. This could be explained if there had been a wind out of the east, but there was no wind measured or discernible. It is noteworthy that, except in one instance, the DU_{LH} is consistent and shows high uniformity.

Since no bias or testing errors were discovered, the course of action used was the average for each irrigation type. For the time based irrigation, each zone was programmed to apply a net of 0.875" per week, using the RTM, which falls between the DU_{LQ} and DU_{LH} values. The run times therefore were the following:

0.875”/0.86iph = 1.017 hours
1.017 hours x 1.26 = 1.28 hours or 77 minutes per week, 39 minutes per run day
For the ET based irrigation 0.88 inches/hr is the precipitation rate and the Landscape Coefficient (K_L) is 0.8 (K_S=0.8, K_D=1.0, K_{MC}=1.0).

Data Recording and Reporting

Water meters are read and recorded monthly. Photos of each plot are taken monthly with a brief description of the observed quality of the turf in each plot, and a log is maintained to record mowing, fertilization, pest management, irrigation schedules of each plot and any irrigation system maintenance (adjustment of sprinklers, etc).

Observations

Figure 2 shows the monthly readings of the water meters for each of the irrigated plots. The zone number and meter number are indicated as well as the total monthly run time

IRRIGATION TEST PLOT STUDY

WATER METER READINGS 1-Jul 31-Jul-12

ET irrigated test plots

Meter #	Zone number	Ending reading 31-Jul-12	Begining reading 1-Jul-11	Total gallons
71089660	8-16	10,361.5	10,013.2	348.3
71089661	8-17	11,542.5	11,175.2	367.3
71089663	8-18	10,365.1	10,005.9	359.2
71089665	8-19	9,147.4	8,823.7	323.7

Time irrigated test plots

Meter #	Zone number	Ending reading 31-Jul-12	Begining reading 1-Jul	Total gallons
71089666	8-20	12,476.5	11,690.5	786.0
71089667	8-21	12,932.0	12,235.9	696.1
71089668	8-22	12,328.4	11,678.2	650.2
71089669	8-23	13,094.7	12,411.0	683.7

ET irrigated test plots average total run time (min) per zone 1 July 12:01am to 31 July 11:59pm:	Timed irrigated test plots average total run time (min) per zone 1 July 12:01am to 31 July 11:59pm:
154	**273**

Figure 2. Water Meter Readings

Figure 3 shows the average turf quality trends over time. As expected the irrigated plots have a higher quality then the control plots by a visible amount. The irrigated plots track close to the same, but the ET plots at times show a slightly higher turf quality rating. In reality, both irrigation schedules are providing an acceptable quality of turf.

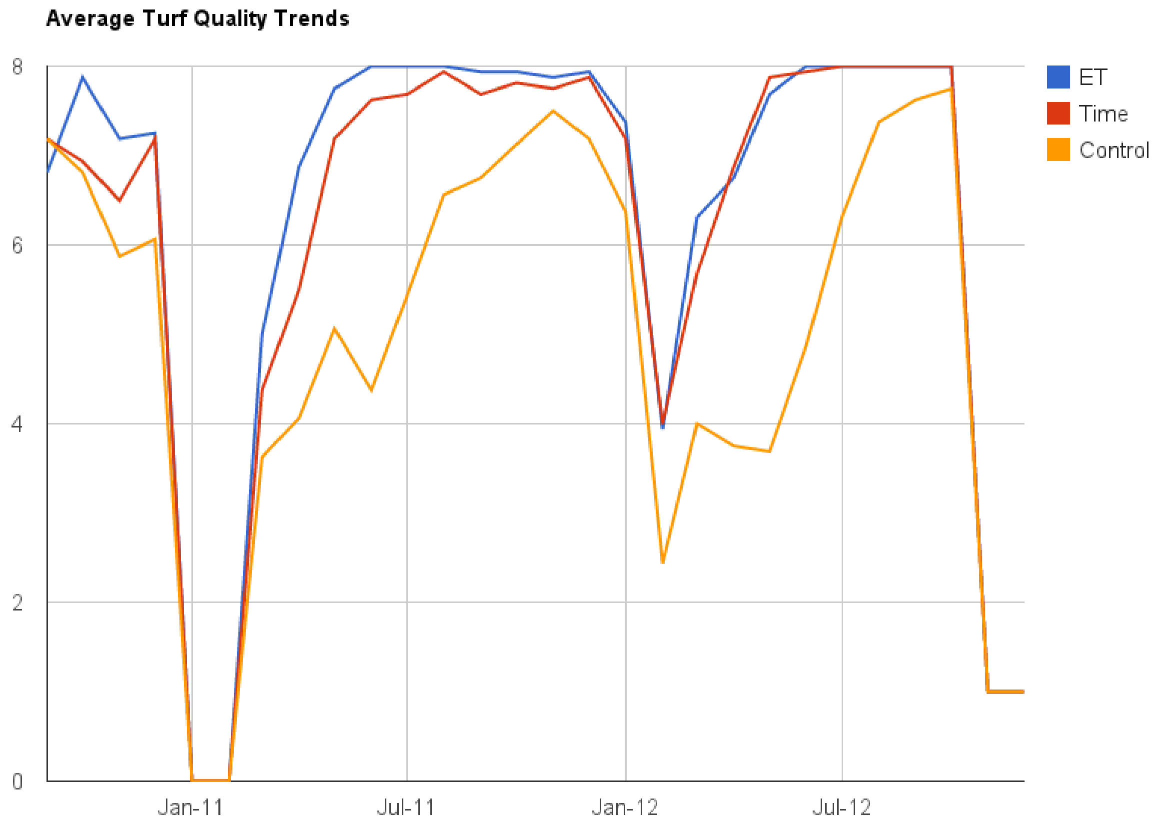

Figure 3. Average Turf Quality Trends

Figure 4 shows the monthly run time average for the two different scheduling scenarios over the last two years. In all 24 months the graph shows that the timed irrigation operated longer than the ET based scheduling. The graph also shows that during the months of May, June and July the two schedules are closer together, time wise, compared to the rest of the year. The difference is significant as in some months the timed plots are operating over 100 minutes more.

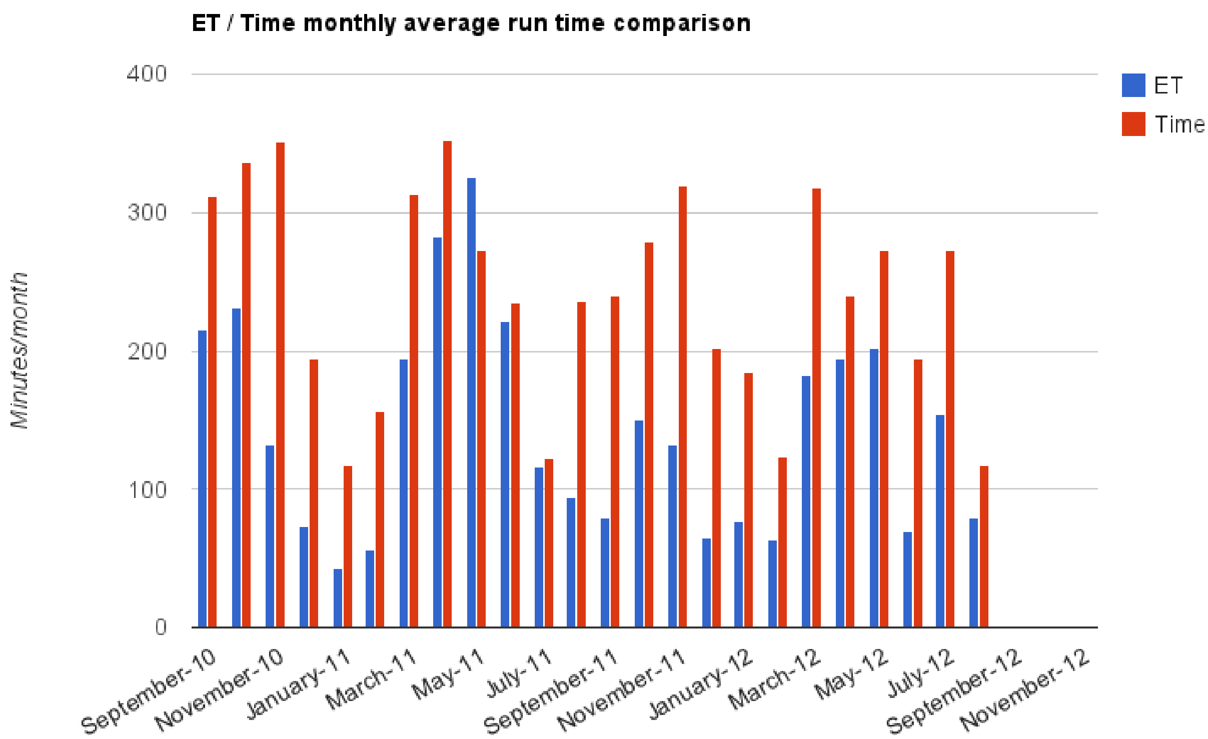

Figure 4. Run Time Comparison

Figure 5 shows the monthly average water use between the two types of scheduling. The figure shows that except for two months in the spring or 2011, the ET based controllers used less water than the timed based scheduling. This is not unexpected as the ET based controlled are designed to match the weather and the timed based to just put down a certain amount of water. Timing on the timed based controllers is based on current water restricts as described previously.

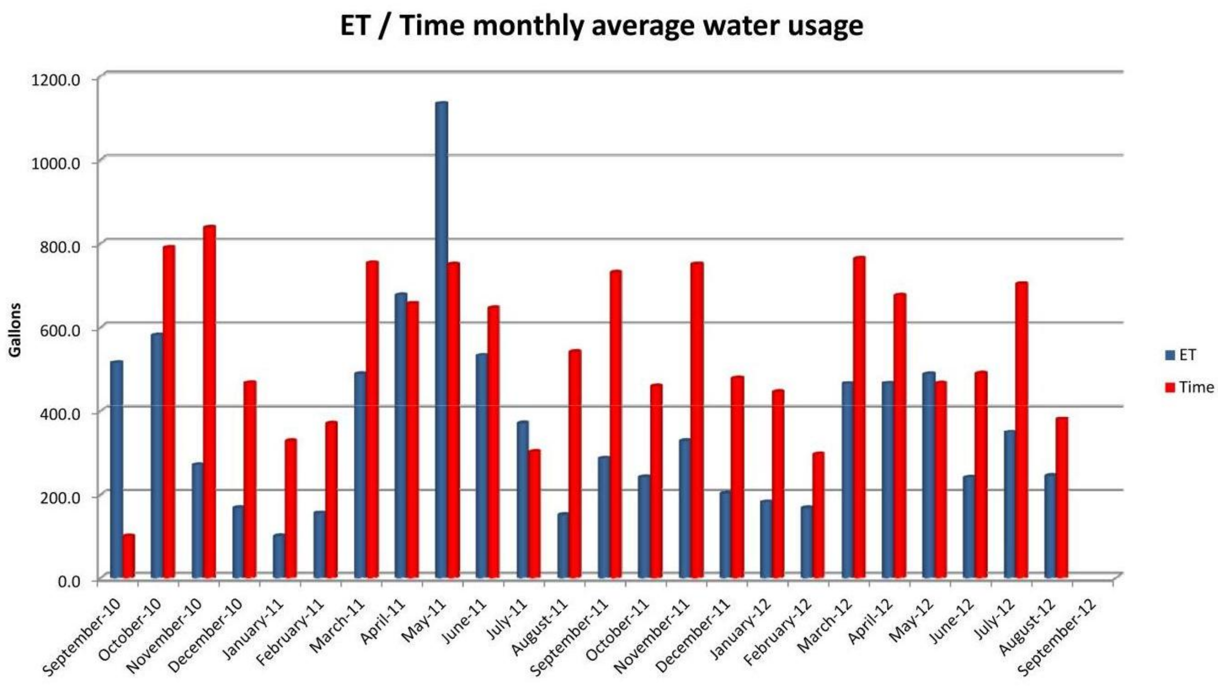

Figure 5. Average Water Usage

Figure 6 shows the cumulative water use of the two systems over the two years. The graphs show that the ET based plots have used approximately 8,000 gallons and the timed plots over 12,000 gallons. This represents over a 33% water savings over the last two years with some months saving more than 50%.

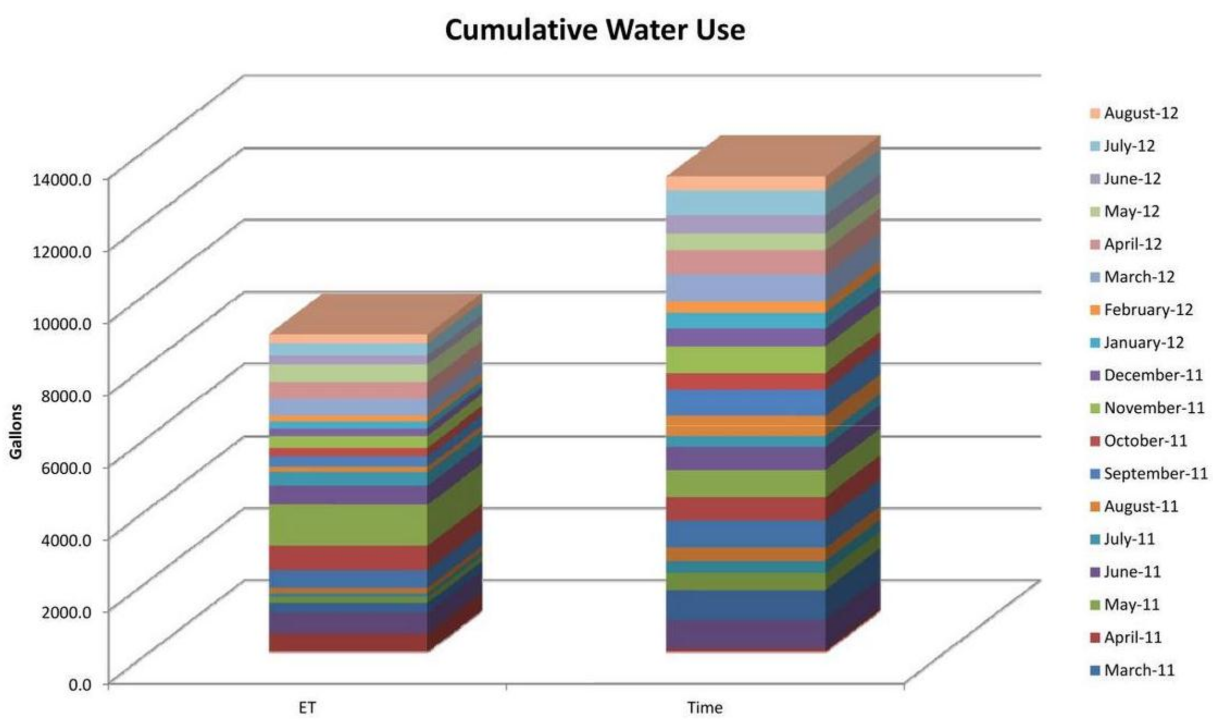

Figure 6. Cumulative Water Use

Conclusions

The study shows that the ET based control system saves significant water over the mandated schedule. Rarely does the ET based schedule use more water than the time based schedule. The ET based schedule also better matches the weather making it more realistic. The quality of the turf is similar between the two different schedules. The overall operating time on the ET based schedule is much lower which reduces the overall water window and wear and tear on equipment. Although this study utilized a sophisticated onsite weather station, one could surmise that ET based controller should have similar water savings.

FAWN Interactive Irrigation Tool for Florida

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Abstract. *Smart irrigation technologies are available that have been shown to reduce water volumes applied to landscapes while maintaining landscape plant quality as compared to standard time-based automated irrigation systems. To encourage the use of these technologies, a new web-based interactive irrigation tool has been developed for homeowners, irrigation professionals, and others to investigate the different irrigation technologies using site-specific and real-time data from the Florida Automated Weather Network (FAWN) stations. The model simulates a water balance in a lawn environment including soil water, rainfall, evapotranspiration, infiltration, runoff, percolation, and irrigation on a daily time step. Model results are reported to the user weekly via email. The model simulates different irrigation technologies including time-based scheduler, time-based plus rain sensor, time-based plus soil moisture sensor, and evapotranspiration controller. Model output includes the water applied that is not used by the lawn as a percentage and volume. Model coding accuracy was verified and outputs were validated from two Florida study sites. The tool, hosted on the FAWN web site, is meant to provide a virtual environment to explore new irrigation technologies so that potential users can better understand their operational differences and potential water savings.*

Keywords. Irrigation, turf, lawn, soil moisture sensor, evapotranspiration

Introduction

Turfgrass growth occurs during warm months when rainfall may not meet plant growth needs resulting in water stress. Since aesthetics and health are primary factors for many turfgrass owners, irrigation systems are often implemented to supplement plant water needs. Irrigating turfgrass has evolved from manual hose-and-sprinkler systems to automated irrigation systems which tend to over-water, resulting in decreased turf quality and water wastes (Trenholm and Unruh, 2005). Mayer et al. (1999) indicated that 47% more water may be used by automated irrigation systems compared to non-automated systems (or manual systems) for landscape irrigation due to a “set-and-forget” mentality.

The inefficiency of automatic irrigation systems has led to the development of technologies that use rain sensors (RS), soil moisture sensors (SMS), and/or evapotranspiration (ET) controllers to improve irrigation application to meet plant needs. These irrigation technologies have been branded as “Smart Controllers” (Irrigation Association, 2007). Several studies have shown water savings associated with these Smart Controllers compared to conventional time-based irrigation scheduling (Davis et al., 2007; Haley and Dukes, 2007; Shedd et al., 2007; Cardenas-Laihalcar et al., 2008; Dukes et al., 2008; Dukes and Haley, 2009; McCready et al., 2009; Cardenas-Laihalcar et al., 2010; Cardenas-Laihalcar and Dukes, 2010; Davis and Dukes, 2010; McCready and Dukes, 2011). The concept behind Smart Controllers is to irrigate based on the soil water deficit, by either sensing soil water content (SWC) or estimating ET, so that the SWC is restored to a certain percentage of field capacity (FC).

Irrigation systems with RSs, SMSs, and ET controllers are all used to improve the estimation of irrigation needs based, in some regards, on the concept of a soil water balance (Allen et al., 1998):

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_{net,i} - CR_i + ET_{c,i} + DP_i \qquad (1)$$

where D_r (mm) is depletion of water from root zone, i is the current day, i – 1 is the previous day, P (mm) is daily precipitation, RO (mm) is runoff, I_{net} (mm) is net irrigation depth, CR (mm) is capillary rise from the groundwater table, ET_c (mm) is crop ET and DP (mm) is deep percolation (PERC) (Allen et al., 1998). Depending on the technology used, different components of Eq. 1 are considered. The SMS controls irrigation solely on a D_r field measurement. The ET controller generally estimates D_r using input data and P and ET estimates to calculate I. RSs use P to bypass I. Thus, there is potential to simulate how these technologies would operate based on this relationship and user input.

Currently there is no simple virtual simulation of this concept where Floridians can evaluate different irrigation technologies before investing in modifications of their irrigation system. The objectives were to (1) develop a simple model to simulate the soil water balance based on site-specific soil characteristics, irrigation schedule, real-time weather data, and irrigation device and (2) provide homeowners and landscape professionals with an interactive tool to evaluate and improve irrigation scheduling.

Methods

A simple, one-dimension soil water balance model was designed to simulate water movement in the root zone of turfgrass in a typical Florida lawn. We included processes of I, R, ET, runoff (Q), and PERC. The model simulates a daily timestep with all variable units evaluated as depth (i.e., cm). The SWC was calculated based on water gains (i.e., R, I) and losses (i.e., ET, Q, PERC) to the initial SWC quantity in one soil layer (root zone) as follows:

$$SWC_i = SWC_o + R_i + I_i - ET_{a,i} - Q_i - PERC_i \qquad (2)$$

where i is the current day and ET_a (cm) is actual ET. Actual ET was calculated as the product of the reference ET (ET_o, cm) from the Florida Automated Weather Network (FAWN) and a crop coefficient (K_c) from Jia et al. (2009). Detailed information on model development can be found in Dobbs (2012).

Four different irrigation technologies were simulated by the model: time-based scheduler, time-based plus RS, time-based plus SMS, and ET controller. The primary difference in model simulation among the irrigation technologies was the irrigation application depth. This was simulated by requiring specific input parameters for each technology in addition to a scheduled irrigation depth (required for all options).

The model output included daily and weekly water volume applied (I + R), water volume not used by the turfgrass (Q + PERC), depths of water leached and lost to runoff, and water stressed days. Volumes of water applied were determined using the irrigation depth applied and the irrigated area input. Water volumes not used by the landscape was calculated by adding PERC and Q depths and multiplying by the irrigated area input. Water stress was calculated using the management allowable depletion (MAD) concept. The MAD was considered to be 50% of the available water (AW). Available water is the amount of water stored in the root zone that is available to the plant (Eq.3). According to Allen et al. (1998), a MAD value between 40% and 60% is typical for turfgrass irrigation.

$$AW = (FC - WP) \times RD \qquad (3)$$

where FC is field capacity, WP is wilting point, and RD is rooting depth. Thus, water stress occurred for a day if the SWC was less than MAD or 50% of AW.

Model results were validated using two datasets collected in Florida in plot studies. Irrigation applied, water volumes leached, and rainfall were compared between the model and the measured data. Computational accuracy was tested or verified using a Microsoft Excel model and a program written in Java to mathematically simulate the model. The Java program was used to create the graphical user interface (GUI), hosted by Google App Engine (Jie Fan, FAWN, personal communication, 7 March 2012). The GUI generated output in comma separated files so that equal input values in both Excel and the GUI could be compared for various scenarios.

The “Interactive Irrigation Tool” GUI was developed to be simple and engaging for the user. The following inputs were required: unit system (English or metric), RD (input value or default was 30 cm), soil type (select one of six types; default was sand), irrigated area (input value or default is 0.10 ha), irrigation system (select one of four choices; default was time-based scheduler), ZIP code, irrigation depth (for all technologies except ET controller). Irrigation depth was input by the user or based on a system runtime (min) and an irrigation system selection of microirrigation (1.27 cm/h), fixed head (3.8 cm/h), gear driven head (1.27 cm/h), or impact head (1.27 cm/h). The soil type was used to determine FC and WP. The ZIP code served two purposes. It linked the model to the closest FAWN station for real-time weather data and it was used to implement water restrictions for Miami-Dade County. Only Miami-Dade County water restrictions were implemented as an example case; current funding limited further state-wide implementation of restrictions in the model. Because of the nature of Miami-Dade County restrictions, a house number was requested to determine watering days for these ZIP codes. Watering days vary by odd/even house numbers in Miami-Dade County with even numbered houses restricted to Sunday and Thursday and odd numbered houses restricted to Wednesday and Saturday (Miami-Dade County, 2012). For ZIP codes outside of Miami-Dade County, the user selected irrigation days.

All inputs on the GUI were assigned default values except for ZIP code and street number. A definition or description was provided for some of the required inputs that were not considered to be common knowledge. These were visible to the user by scrolling over question mark icons located adjacent to the required input. The user was also given the option to subscribe to weekly updates on the virtual lawn via email.

Results and Discussion

The model was validated using two plot study datasets. The irrigation, leachate or PERC, and rainfall data collected in the plot study was compared to model predicted values. Average absolute differences between measured and predicted values ranged from 0.37 cm to 1.62 cm for percolation and 0.0 cm to 0.28 cm for irrigation depths. Results were within expected errors or were explained by inaccuracies in the measured data. A detailed discussion of this process is available in Dobbs (2012).

The computational accuracy of the model was successfully simulated by generating equal output in Microsoft Excel and a Java written program. The GUI was successfully launched online 1 March 2012. The tool can be found on the FAWN web site at http://fawn.ifas.ufl.edu/tools/interactive_irrigation_tool/. The GUI was designed with the assistance of the FAWN team at the University of Florida and is currently maintained by their staff. Because the tool was built on Google technology, an active Google account is required. The user is prompted for a Google username and password after selecting the link. Once signed in, the user is directed to the GUI. Data entries required by the GUI include units, soil characteristics, irrigation technology used, irrigation schedule, and irrigation amount (unless ET controller is selected). Entry boxes appear depending on previous input values or technology selection. For all irrigation technologies options except ET controller, irrigation amount applied per event is entered as either depth per event or based on the selection of irrigation system type (i.e. microirrigation [1.27 cm/h], fixed head [3.8 cm/h], gear driven head [1.27 cm/h], or impact head [1.27 cm/h]) and a system runtime entered. If the "Time-based plus rain sensor" is selected, the rain sensor setting is also required. If the "Time-based plus soil moisture sensor" is selected, the threshold value is also required.

After the user has submitted all of the required values, an email is sent to the user with information including the amount (volume) and percentage by which the irrigation system overwatered and the number of days for which the turfgrass did not receive enough water. Based on these values, the lawn is ranked on a scale of one to five, one representing an efficient irrigation system and five inefficient. The scale also corresponds to a color of the virtual lawn (dark green [rating equal to one] to light brown [rating equal to five]). The email also displays the distance between the user's ZIP code and the FAWN station.

Conclusions

The model successfully simulated I and PERC amounts for time-based irrigation, time-based with RSs, time-based with SMSs, and ET controllers. The model was integrated into a GUI tool that is available, free of charge. Additional work on the model will be conducted as funding allows. Particular improvements include a more user friendly interface, options to investigate multiple irrigation scenarios at one time, and inclusion of more rainfall data collection sites.

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A method to estimate irrigation in residential areas: a case study in Orlando, Florida

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Abstract. *A methodology to estimate residential irrigation using monthly metered total water use and irrigation data is presented here. In this work 2,142 homes located in Orlando, Florida, were analyzed. The analysis was based on monthly billing records for the period 2006-2009. Annual total water use and actual irrigation were calculated. This work is based in a previous study where residential irrigation was estimated based on total monthly water use billing records, basic indoor water use using two different methods (minimum month and per capita methods), and estimating the irrigable area using three different percentages of impervious areas covering the green area. The results of this study showed that actual irrigation accounted for 63.8% of the total water use. Average total water use was 18,591 gal month^{-1} and average actual irrigation was 12,087 gal month^{-1}. Also, indoor water use was fairly constant across the year with an average of 6,504 gal month^{-1}. Coefficients of determination (R^2) between actual and estimated irrigation for monthly and annual values ranged between 0.6086 and 0.9991. Monthly and annual equations to estimate irrigation from total water use are presented in this paper, but their applications are recommended for de area of Central Florida.*

Keywords. Actual irrigation, total water use, indoor water use, Florida.

Introduction

There is an increase in the use of irrigation for urban landscapes (Ferguson, 2007). Irrigation water use is the greatest single source of household water consumption (Mayer et al., 1999; Perez et al., 2004), and, as water availability decreases, it is important that landscape managers and homeowners recognize that they are responsible for how water is applied in order to be conserved (Devitt and Morris, 2008). USGS estimated that, during certain times of the year, 25-75% of residential water use is for outdoor purposes (primarily lawn watering) in Florida (DEP, 2010). A study based on 27 cooperating residential homes in Central Florida reported that 64% of the residential water use volume accounted for irrigation in a 30 month period (Haley et al., 2007). A different study conducted in homes encompassed by City of Tampa Water Department (TWD) and Orange County Utilities (OCU) concluded that 25-35% of the homes in Tampa and 53-60% of homes in Orlando over-irrigated during a period from 2003 through 2007. This study was based on an estimation of irrigation in single-family homes using billing records of monthly total water use (Romero and Dukes, 2012).

There is little information about how much water is used for both outdoor and indoor purposes in the U.S. especially quantitative analysis for irrigation purposes (Mayer et al., 2003; Palenchar et al., 2009). Irrigation can be accurately measured by installing dual water meters at residential homes, a main water meter and an irrigation meter. A utility company installs the main water meter within the main water inlet pipe, and is used to determine the total amount of water used by the household for billing purposes. Then the irrigation meter is connected to the utility main pipe that will measure only the irrigation water use (Haley and Dukes, 2010). Otherwise, irrigation is typically estimated by subtracting the indoor water use from the total metered water use consumption (Mayer et al., 1999). One assumption is to consider the winter low water use as a representative indoor use only (Dziegielewski and Kiefer, 2009). This approach works well and gives a baseline for outdoor water use in areas where winter is well defined, but in areas like Florida where there is no clear winter season this approach may over-estimate indoor use (Haley and Dukes, 2007).In warmer areas, like Florida, the minimum month method could adjust better (DeOreo et al., 2008, Mayer et al., 2009). Another approach is the per capita method (Mayer et al., 1999). To apply this method, an estimated value of indoor water use per capita per day is multiplied by the average number of inhabitants in a household, by 30 days.

The objective of this paper is to validate a methodology to estimate irrigation from total water use using observed irrigation data for a selected group of homes in Orlando, Florida.

Materials and Methods

Water use data base and quality control

Monthly total water use billing records of 2,142 households located in Orlando, Florida, were available from Jan 2006 through May 2009. Monthly irrigation records for the same homes were available too. These homes had separate total and irrigation water meters. Additional information available were customer name, address, parcel area, built area, date. A quality control procedure was performed on the database, where missing and/or negative values in the categories of total water use, irrigation water use, parcel area, and built area, were not considered in the analysis. Both, annual total water use and annual irrigation were also calculated by adding the corresponding monthly values (January through December) at each household, since annual data was not available in the water use billing records.

Determining total water use, actual irrigation, and indoor water use

Total water use data for the period 2006 through 2009, and their corresponding actual irrigation were used to calculate indoor water use by simple subtraction (indoor use = total water use – actual irrigation). These data were categorized by months (e.g. January, February, etc.) and the results were analyzed. The annual values were aggregated into one database and their results also were analyzed. The observed monthly indoor use results were compared to those values obtained by using two standard methods to estimate indoor water use: the per capita and the minimum month methods. In the per capita method an estimated value of monthly indoor water use is obtained by multiplying the indoor water use per capita per day, times the average number of inhabitants per single-family home, times 30 days. The number of inhabitants per home was estimated at 2.25 for Orlando (Mayer et al. 1999; U.S. Census Bureau 2009). Mayer et al. (1999) estimated an indoor water use of 66.1 gallons per capita per day for Central Florida, giving as a result 4,462 gal month^{-1}. In the minimum month method (Mayer et al. 1999) the lowest-use month in a year was assumed to represent indoor use and all differences between the other months and the lowest-use month value were considered to be outdoor use. This method is based on the assumption that indoor use remains fairly consistent across season (Mayer et al., 1999). Our previous study (Romero and Dukes, 2012) showed that the lowest use month ranged from 5,221 to 13,115 gal $month^{-1}$, representing the indoor uses for Orlando area, from 2003 through 2007.

Irrigation estimation

Irrigation was estimated on a monthly basis in order to compare the obtained values with the actual irrigation. Annual estimated irrigation was also determined for the analysis. We used the methodology presented by Romero and Dukes (2012). To estimate irrigation, the basic monthly indoor water use determined by the per capita method was subtracted from the monthly metered water use. The resulting values were divided by an estimated green area, which was obtained by subtracting the building area from the parcel area. An assumed impervious area was subtracted from the green area to finally obtain the irrigable area. Since we considered three impervious areas scenarios (5, 15 and 20% from total green area) we obtained three estimated irrigation values per home. We will show the results using 15% impervious area, but a discussion about differences among the three values is shown.

Comparison of estimated and actual irrigation (Jacknife analysis)

The estimated and actual monthly irrigation values were aggregated by month, which included data from 2006 through 2009. A sample equivalent to 70% of the estimated irrigation data was used and compared against their corresponding actual irrigation to determine the regression equations and regression coefficients for each month. These equations were used to estimate new monthly irrigation values (or 'corrected irrigation values') on the remaining 30% of the data for each month. The new corrected estimated irrigation values were compared against actual irrigation and their new regression coefficients were analyzed (Jacknife analysis; Wu, 1986). In Jacknife analysis, new estimates are compared against actual measured values for a set of data different from those used as input data. The same procedure was performed with the annual irrigation data.

Equations to calculate irrigation from total water use

Regression analyses were carried out between actual irrigation and property characteristics (including total water use, parcel area, built area, green area) to understand the relationship between the dependent variable (actual irrigation) and the rest of parameters. R^2 and F-values (significance of the equations) were analyzed. Equations to calculate actual irrigation are presented for each month and for a year.

Results and Discussion

Water use data and quality control

After the data quality control, the initial number of homes (2,142) was reduced depending on the annual or monthly aggregation. The total number of households per year ranged from 539 to 1781. For the monthly analysis, the number of households ranged from 1392 to 1816 (Table 1).

Table 1: Number of households evaluated in the present analysis

		N° of homes
Year	2006	539
	2007	1,182
	2008	1,781
	2009	1,722
Months	Jan	1,722
	Feb	1,729
	Mar	1,786
	Apr	1,818
	May	1,816
	Jun	1,570
	Jul	1,392
	Aug	1,464
	Sep	1,507
	Oct	1,607
	Nov	1,653
	Dec	1,707

Total water use, actual irrigation and indoor water use

Monthly and annual total water use, actual irrigation and indoor water use are shown in Tables 2 and 3. The maximum average monthly total water use was observed in May at 22,887 gal month^{-1}, while the minimum was observed in the month of February, at 16,006 gal month^{-1}. The average actual irrigation ranged from 9,347 to 16,051 gal month^{-1} in July and May, respectively. Maximum total water use and irrigation values were observed in May, when temperature starts increasing but rainfall amount is not as high as in the coming months (Jun-Sep). Minimum values for total water use and irrigation is also observed in a warm month (July) where rainfall amounts is higher than the rest of the months. The average indoor water ranged from 5,812 to 7,154 gal month^{-1}, in February and August, respectively. Clearly, the statement said by Mayer et al. (1999) about indoor use remains fairly consistent across season can be observed in these monthly data. These actual indoor use values were lower than our previous findings using the minimum month method. In our previous study (Romero and Dukes, 2012) we found that the lowest-use months ranged from 5,221 gal month^{-1} in 2005 to13,115 gal month^{-1} in 2006, with an average of 9,479 gal month^{-1} for the period 2003 through 2007 in the same study area (Orlando). The minimum month method estimated 2,975 gal month^{-1} more indoor water use than what was observed. The per capita method gave an indoor value of 4,462 gal month$^{-1,}$ which seems to be under-estimated compared to the actual indoor use.

The average annual total water use was 130,359, the average annual actual irrigation was 83,172, and the average annual indoor use was 47,187. In this study, actual irrigation water use accounted for 63.8% of the total water use. This is supported by Haley et al. (2007) showing that more than 50% of the total household water use is for irrigation purposes. Romero and Dukes (2012) estimated that 68.3% of the total water was used for irrigation purposes when the per capita method was used to calculate indoor water use. When the minimum month method was applied, only 32.6% of the total water was used for irrigation purposes. With our current results we can say that the minimum month method can over-estimate indoor water use and as a consequence under-estimate irrigation water use.

Table 2: Average monthly values of total water use, actual irrigation and indoor water use

Month	Avg. total water use	Avg. actual irrigation	Avg. indoor use
		gal $month^{-1}$	
Jan	17,088	10,670	6,417
Feb	16,006	10,193	5,812
Mar	19,213	12,586	6,627
Apr	22,560	15,871	6,689
May	22,887	16,051	6,835
Jun	17,949	11,739	6,211
Jul	15,634	9,347	6,287
Aug	18,952	11,798	7,154
Sep	17,257	10,850	6,407
Oct	18,606	12,042	6,564
Nov	18,684	12,250	6,434
Dec	18,258	11,646	6,613
Average	**18,591**	**12,087**	**6,504**

Table 3: Average annual values of total water use, actual irrigation and indoor water use

Month	Avg. total water use	Avg. actual irrigation	Avg. indoor use
		gal $year^{-1}$	
2006	89,117	57,782	31,335
2007	177,043	116,328	60,715
2008	164,305	100,443	63,861
2009	90,972	58,136	32,835
Average	**130,359**	**83,172**	**47,187**

Comparing estimated against actual irrigation

The monthly estimated irrigation values were compared against the monthly actual irrigation values to analyze the relationship between these two datasets. Table 4 (column on the left) shows the coefficients of determination (R^2) obtained by plotting a sample of 70% of data from the estimated and actual irrigation databases. R^2 ranged from 0.7562 to 0.8419, and these values corresponded to the months of September and June, respectively.

Table 4: R^2 values for monthly curves comparing estimated irrigation versus actual irrigation.

Month	R^2 (Estimated irrigation vs. actual irrigation)	R^2 (Corrected estimated irrigation vs. actual irrigation)
Jan	0.8015	0.8012
Feb	0.7942	0.8487
Mar	0.8095	0.8298
Apr	0.7970	0.9991
May	0.8177	0.9974
Jun	0.8419	0.8437
Jul	0.7858	0.7902
Aug	0.7576	0.6846
Sep	0.7562	0.7683
Oct	0.8005	0.6154
Nov	0.8082	0.7300
Dec	0.8234	0.6086

Figure 1 (column ‘a’) shows the resulting curves, linear regression equations, and R^2 values from comparing actual irrigation and estimated irrigation using 70% of the data for 6 months of the year. There are few irrigation values that are over-estimated. All R^2 values were higher than 0.7500. The remaining 30% of the data were used to correct the estimated irrigation values by using the equations previously obtained. The corrected estimated irrigation values in most of the cases showed higher R^2 values than those obtained during the initial comparison, ranging from 0.6086 to 0.9971. R^2 were lower for the winter months, as these can be observed in Table 4 (column on the right). Some of the new corrected irrigation values are over-estimated.

Figure 2 (a) shows the comparison between actual annual irrigation and estimated annual irrigation using 70% of the total data. The R^2 was 0.7982. The corrected annual estimated irrigation values (calculated with the remaining 30% of the data) were plotted against the actual annual irrigation and R^2 obtained was 0.7984. Both trends were similar.

The effect of the percentage of impervious area on the estimated irrigation was as follows: it increased 6% when 20% impervious area was used compared to 15% impervious area; and it decreased 10% when 5% impervious area was used (also compared to 15% impervious area; Romero and Dukes, 2012). When plotted against actual irrigation, the three coefficient of determination values were the same (R^2 = 0.7977), and according to the linear regression equations the actual irrigation is approximately 58 to 69% of the estimated irrigation.

Equations to calculate irrigation from total water use

Equations to estimate monthly and annual irrigation are shown in Figures 3 and 4. These equations show irrigation as a function of total water use only. The units are in gallons $month^{-1}$ and gallons $year^{-1}$. Regression analyses between actual irrigation and property characteristics such as parcel area, built area and green area did not show good coefficients of determination (R^2) and the regression equations were not significant (Table 5). Monthly and annual equations to calculate irrigation from total water use were significant at 99% and then we can accept these equations.

The monthly equations are recommended due to the seasonal variability of temperature and rainfall in the area, so the estimated irrigation values can be more reliable. However, a general annual equation is also recommended. The application of these equations is recommended to the Orlando area only. The results obtained by using these equations with total water use records from locations other than Orlando must be always be used with caution since the conditions for their determination are unique for Central Florida.

Table 5: Regression analysis results between actual irrigation and property characteristics.

	Coef. of determination (R^2)	Significance F
Actual irrigation vs. total water use	0.8701	0
Actual irrigation vs. parcel area	0.0496	3.705E-178
Actual irrigation vs. built area	0.0237	4.7479E-85
Actual irrigation vs. green area	0.0454	1.1149E-162

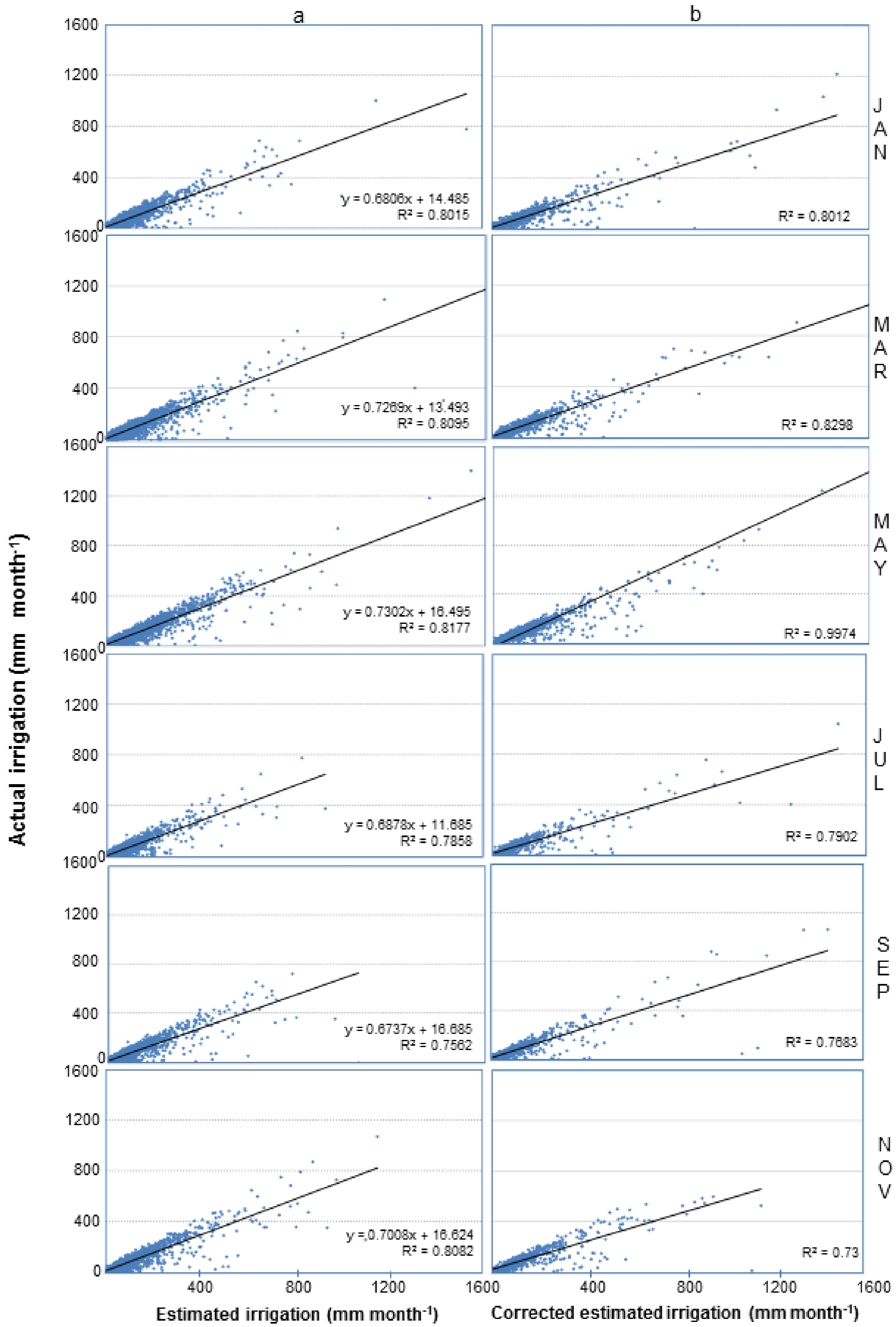

Figure 1. Comparison between actual irrigation and (a) estimated irrigation and (b) corrected estimated irrigation.

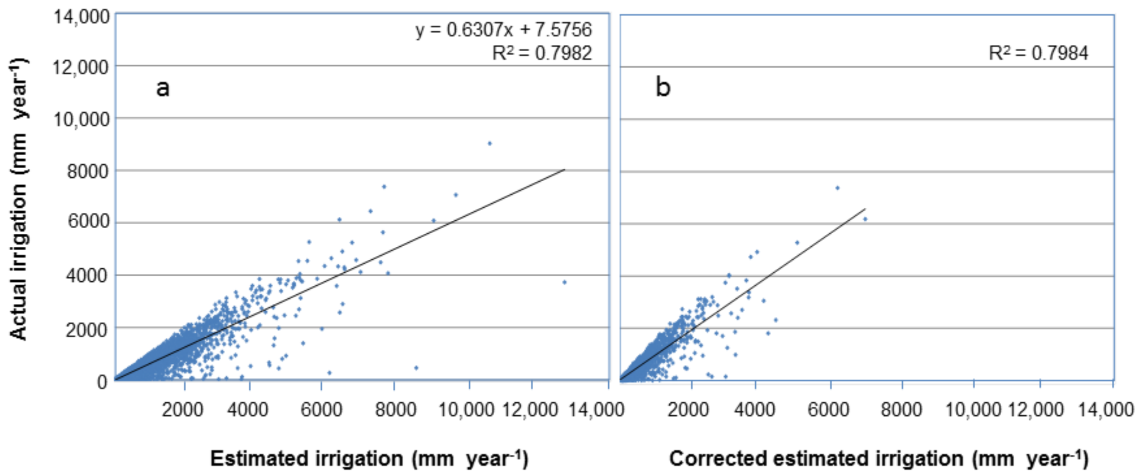

Figure 2. Comparison between actual annual irrigation and (a) estimated annual irrigation and (b) corrected annual irrigation.

Conclusions

Total water use billing records as well as actual irrigation records for 2,142 homes in Orlando, Florida, were available and analyzed to estimate irrigation. Maximum average monthly total water use was 22,887 gal month^{-1} for the month of May, while minimum was observed in the month of February, at 16,006 gal month^{-1}. Average actual irrigation ranged from 9,347 to 16,051 gal month^{-1} in July and May, respectively. Average indoor water ranged from 5,812 to 7,154 gal month^{-1}, in February and August, respectively and values remained fairly consistent across season. Actual irrigation water use accounted for 63.8% of the total water use.

Seventy percent of the data was used to compare and establish the relationship between estimated irrigation values and actual irrigation by getting linear regression equations. The monthly analysis gave R^2 that ranged from 0.7562 to 0.8419. The annual analysis gave a R^2 of 0.7982. The corrected estimated irrigation values plotted against the actual irrigation and their R^2 values ranged from 0.6086 to 0.9971.

Monthly and annual equations to estimate irrigation are shown in this paper as a function of total water use (in gal month^{-1} or gal year^{-1}). The application of these equations is recommended to the Orlando area only.

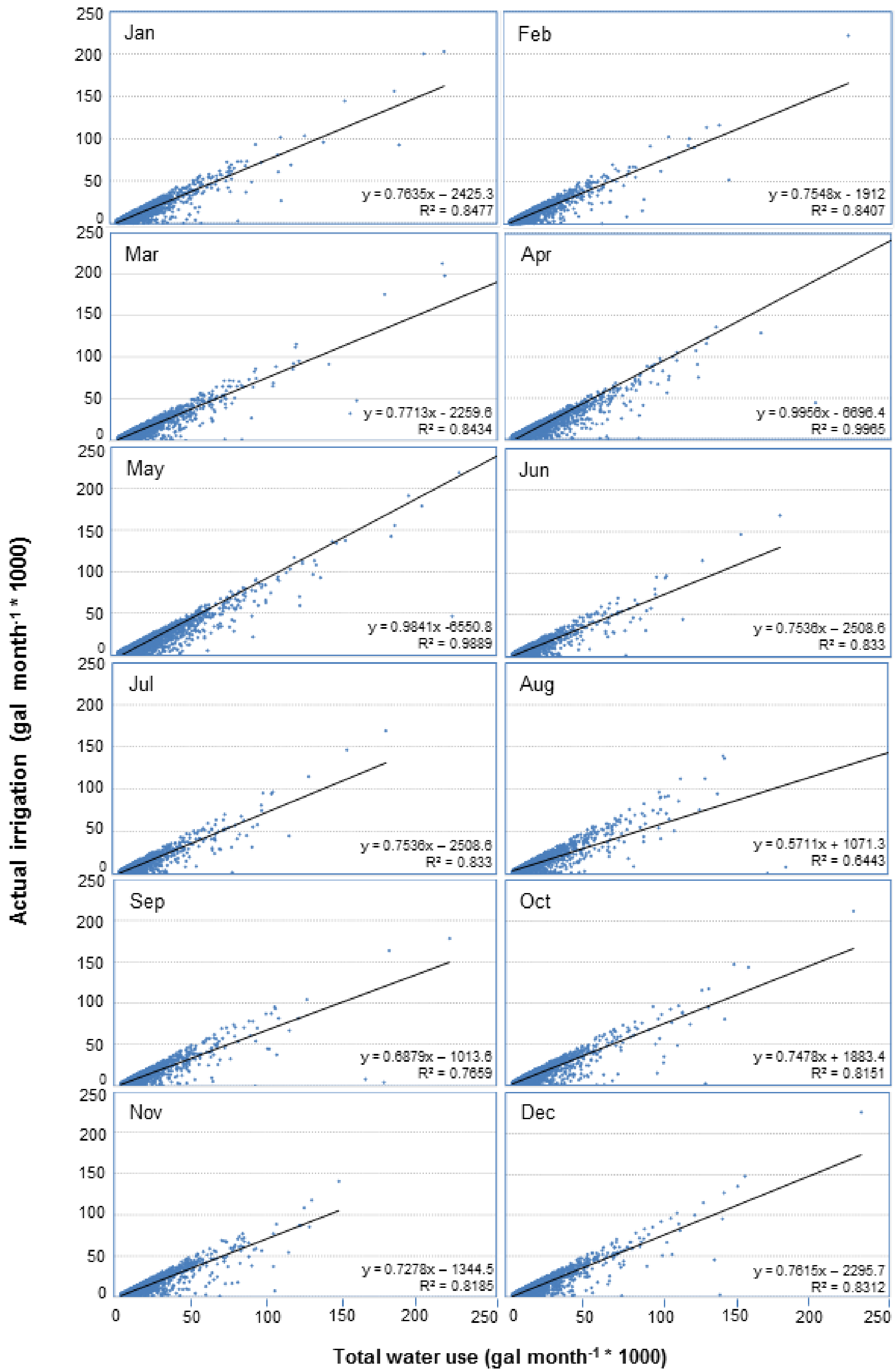

Figure 3. Monthly equations to estimate actual irrigation from total water use.

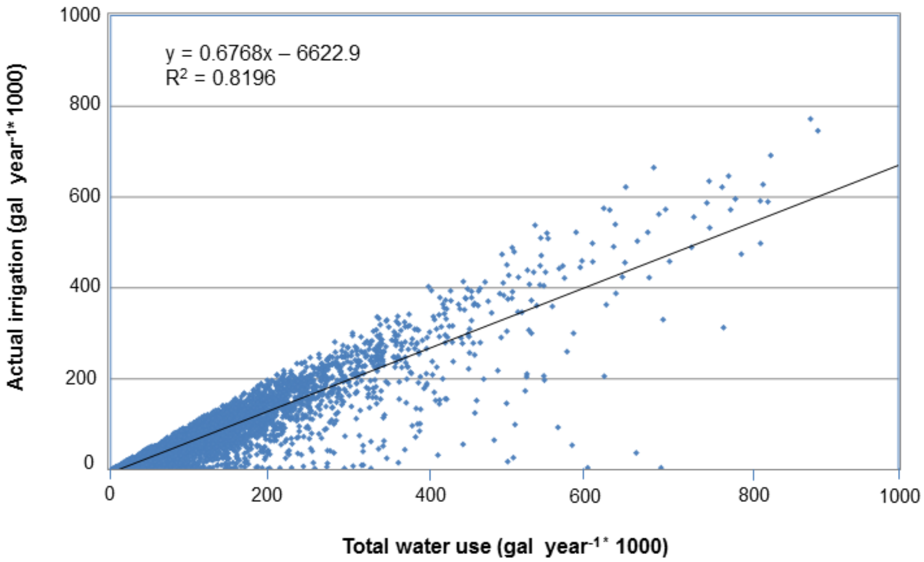

Figure 4. Annual equation to estimate actual irrigation from total water use.

Acknowledgements

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Implementation of Smart Controllers in Orange County, FL: Results from Year One

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Abstract. *It is hypothesized that implementing smart controllers on irrigation systems of known high water users can aid in reducing the overall potable water demand. The objective of this study was to evaluate two types of smart controllers to determine whether they can reduce irrigation application of constituents in the Orlando Metropolitan Area. A total of 167 participants were recruited where 66 Rain Bird ESP-SMT ET controllers and 66 Baseline Watertec S100 soil moisture sensors were installed on single-family residential properties grouped in nine locations. Half of the participants receiving smart technologies also participated in a personal, on-site training session about their smart controller provided by the University of Florida that included optimization of program settings and additional educational materials to supplement the user manual. The preliminary results after 9 months indicate that smart technologies can produce water savings for high water users, averaging between 16% and 23%, but maximum savings were achieved with the combination of smart technology and educational training that included site specific programming, averaging as much as 45%. Data collection and analysis is expected to continue through 2014 to determine the long-term performance of smart controllers in central Florida.*

Keywords. Conservation, cooperators, irrigation, smart controllers, turfgrass quality

Introduction

This project was developed to address growing public water demands in Central Florida. The Central Florida Coordination Area Action Plan ruled to limit additional groundwater withdrawals to meet 2013 demands and deny new water permits past 2013 unless supplemental water supplies are found (CFCA, 2010). Orange County Utilities, located within the Central Florida Coordination Area, experienced population growth of over 16% between 2000 and 2006 (USCB, 2006) with a current service area population of over 490,000. The potential for continued population growth past 2013 leads to the need for reducing total potable consumptive use so that demand does not exceed supply.

Multiple University of Florida Institute of Food and Agricultural Sciences (UF-IFAS) field plot studies have shown that smart irrigation controllers have the potential to conserve water by efficiently scheduling irrigation (Cardenas-Lailhacar and Dukes, 2012; Davis et al., 2009; McCready et al., 2009). In Pinellas County, a cooperator study using soil moisture sensors resulted in similar water savings as the plot studies when the technologies were properly installed and programmed (Haley and Dukes, 2012). However, there were only 58 participating cooperators, generally considered a small sample size for cooperator studies, thus making the results less applicable to generalizing to other areas of the state.

The objective of this study was to evaluate two types of smart controllers to determine whether they can reduce irrigation application of constituents in the Orlando Metropolitan Area. Performance results from this study may contribute to future policies and programs concerning smart controllers that would be developed to reduce consumptive water use in the residential sector.

Materials and Methods

There are a total of 167 residential cooperators across the Orange County Utilities service area in nine location clusters. Treatments were distributed within each location so that there are at least three replicates per treatment group. Installations were staggered from March 2011 through January 2012 where a total of 66 Rain Bird ESP-SMT ET controllers and 66 Baseline Watertec S100 soil moisture sensors were installed. Each location cluster had the following treatments: ET controller only (ET), soil moisture sensor only (SMS), ET controller with educational training (ET+Edu), soil moisture sensor with educational training (SMS+Edu), and a comparison group that was monitored only (MO). There were not enough cooperators in Sweetwater Apopka and North Tanner Road areas to implement all treatments, so cooperators were concentrated into the ET+Edu, SMS+Edu, and MO treatments for good statistical results.

Hourly readings of irrigation volume applied were collected for each cooperator using AMR devices installed and maintained by Orange County Utilities. The volume of irrigation was converted to a depth using the irrigable area measured during the initial irrigation evaluations. Irrigation was then totaled into weeks and averaged across treatments. Statistical analyses were performed using Statistical Analysis Systems (SAS) software (Cary, NC) using the means procedure and treatment differences were determined using confidence intervals (α=0.05).

Turfgrass quality ratings were performed seasonally throughout the treatment periods based on a scale of 1 to 9 where 1 represents completely dead turf and 9 represents the perfect turfgrass, with a 5 selected as the minimally acceptable quality for a residential landscape. Statistical analysis of turfgrass quality was conducted with the glimmix procedure where the change in turfgrass quality ratings between rating periods was modeled compared to the difference in cumulative irrigation application and cumulative irrigation required based on weather. Other factors that could affect turfgrass quality were treatment, educational effect, and soil type.

To determine irrigation demand, three weather stations were installed near the cooperator locations around the county to collect climatic data such as temperature, relative humidity, solar radiation, wind speed, and rainfall. Two additional rain gauges were installed in locations that did not receive a weather station. In addition to the installed weather stations and rain gauges, the Florida Automated Weather Network (FAWN) maintains a weather station in the Apopka area that will be used for the Sweetwater Apopka area location. Daily values of reference evapotranspiration (ET_O) were calculated from the weather station data using the ASCE-EWRI standardized ET_O equation (ASCE-EWRI, 2005).

Results and Discussion

An analysis of historical monthly ET_O and rainfall using thirty years of Orlando International Airport weather data was performed to determine normal weather patterns for Orange County. In general, ET_O was more predictable, rarely falling outside of the 95% confidence interval, whereas monthly rainfall was much more variable and frequently fell outside the 95% confidence interval. These results are indicative of the variability of rainfall and the difficulty of predicting irrigation requirements.

As with the thirty years of historical rainfall, monthly rainfall totals from all the weather station locations and the two independent rain gauges varied greatly during the study period. Overall, rainfall was low during the first three months of data collection with a maximum of 0.68 inches in one month compared to historical averages of approximately 2.5 inches per month for all three months. Low rainfall totals during these particular months are not unusual due to being in the dry part of the year; however, these rainfall totals are much lower than historical normal amounts. Significant rainfall events began in multiple locations around April and May 2012, with rainfall totals exceeding the upper confidence interval for the Turtle Creek area with 22.7 inches in June.

Location cluster and soil type were not significant to the statistical model over the November to August period. The comparison group averaged the most irrigation per week (1.19 inches) and was significantly different than all other treatments (Figure 1). Additionally, the ET controller treatments were different from each other, averaging 0.99 in/wk for the ET group and 0.78 in/wk for the ET with education group. The soil moisture sensor treatments, with 0.84 in/wk and 0.68 in/wk for non-education and education, respectively, were also significantly different from each other. As a result, the education component has significantly lowered the average irrigation application for both technologies. However, there were not significant differences between the ET with education and the SMS without education treatments, thus no preliminary conclusions can be drawn concerning the performance of each type of technology.

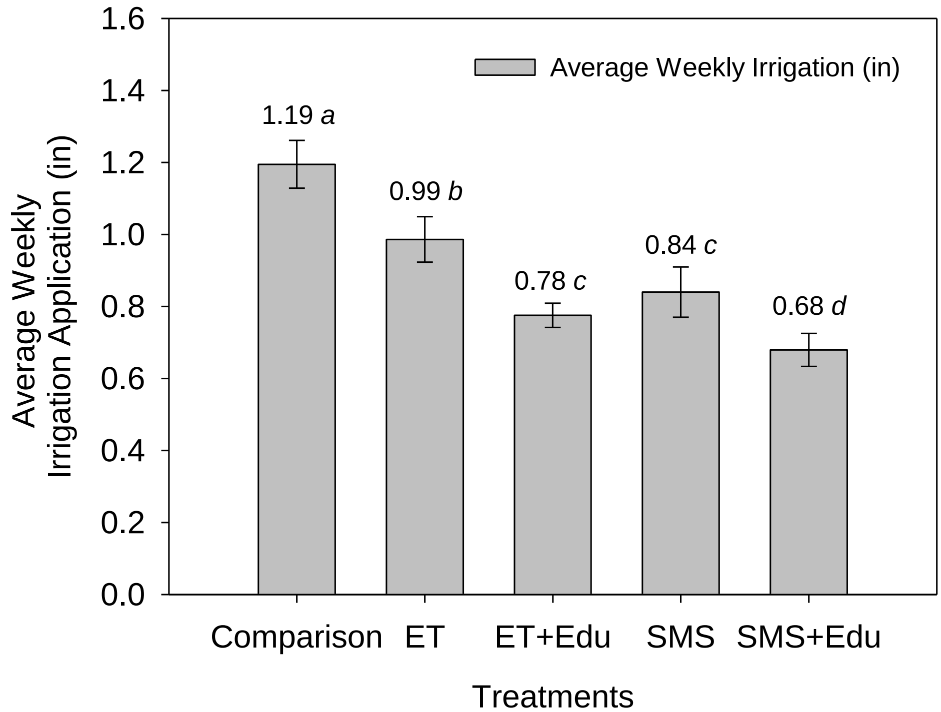

Figure 1. Average weekly irrigation application was calculated for each treatment. The error bars were generated as the 95% confidence interval from the standard error using the means procedure. Treatments were considered significantly different (differences represented as lowercase letters) if the mean value did not fall within the confidence interval of the average weekly irrigation application of the other treatments.

Cumulatively, the comparison group applied the most irrigation, totaling 46 inches, over the nine-month period (Figure 2). The ET and SMS treatments showed similar water savings of 16% and 23%, respectively. Additionally, the ET+Edu and SMS+Edu treatments also showed similar water savings of 38% and 45%, respectively. Overall, there appears to be a trend of water savings due to installing a smart technology with additional savings from education and detailed programming. However, nine months is a too short of a time period for predicting long-term performance.

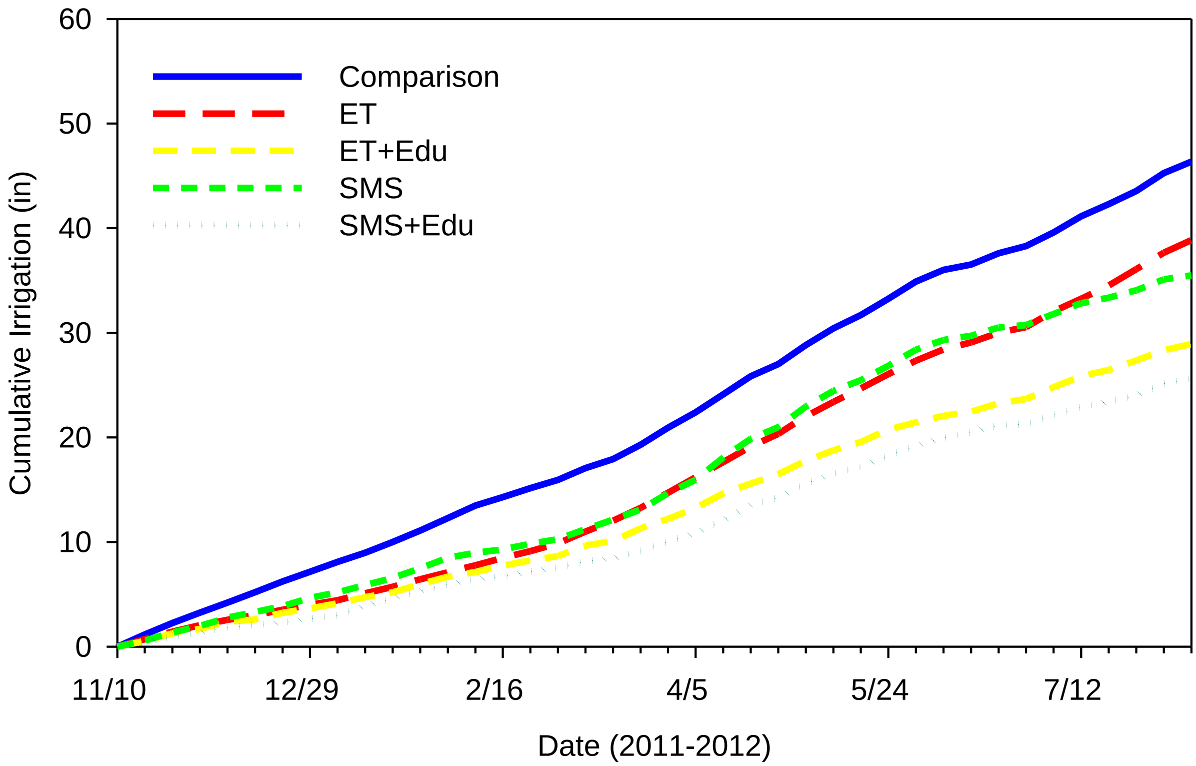

Figure 2. Cumulation irrigation for the study period averaged across locations.

Turfgrass quality ratings were not significantly different based on treatments or due to over- and under- irrigation totals within the same rating period (Table 1). However, ratings varied seasonably with a significant increase in quality for Summer 2012. Rainfall was abundant this summer making it impossible to draw conclusions concerning uncaptured potential water savings despite the increase in average turfgrass quality. Additionally, there was a significant decrease in turfgrass quality for the winter season when some cooperators experienced dormancy while others did not. Other unmeasured factors could affect turfgrass quality such as fertilizer application, mowing practices, and irrigation system maintenance.

Table 1. Turfgrass quality ratings[z] were taken during the initial site evaluation as a baseline as well as seasonally to assess changes in quality due to treatments.

Treatment	Site Evaluation	Fall 2011	Winter 2011-2012	Spring 2012	Summer 2012
Comparison Total	6.3 *abc*	6.3 *a*	6.5 *b*	6.4 *a*	7.6 *c*
ET Total	6.6 *abc*	6.7 *a*	6.2 *b*	6.7 *a*	7.8 *c*
ET+Edu Total	6.4 *abc*	6.8 *a*	6.0 *b*	6.6 *a*	7.7 *c*
SMS Total	6.6 *abc*	6.7 *a*	6.1 *b*	6.5 *a*	7.3 *c*
SMS+Edu Total	6.2 *abc*	7.0 *a*	6.0 *b*	6.7 *a*	7.6 *c*

[z]Different letters within a column and across columns indicate statistical difference at $P<0.05$.

Conclusions

Based on these preliminary results, the smart controllers are showing the potential for water conservation without decline in landscape quality. Average water savings were 16% to 23% for contractor-installed units with increased water savings from additional education and site-specific programming, averaging 38% to 45%. However, assessing the impact of smart technologies on the potable water demand cannot be determined from short-term use. Thus, data collection and analysis is expected to continue through 2014 to obtain a more accurate depiction of smart controller performance in central Florida.

Acknowledgements

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Quantifying Florida-Friendly Landscaping irrigation use in southwest Florida

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Abstract. *The objective of this study was to determine if Florida Friendly Landscaping (FFL), whose actual irrigation use has not been documented relative to typical landscapes, results in reduced irrigation application. Florida Friendly-recognized homes from Hillsborough, Pasco, and Pinellas counties in Florida were compared to representative neighbors with acceptable turf quality selected for each FFL home. A subset of FFL homes that were visibly following FFL principles while maintaining an aesthetically pleasing landscape were then compared to their neighbors. Estimated monthly irrigation use was determined from monthly total water use (potable billing data), an estimate of indoor water use, and an estimate of irrigated area. For both FFLs and comparisons, the means exceeded the medians in all months and a large portion of both groups did not irrigate at all. Florida Friendly Landscaped homes tended to irrigate less than their traditionally-landscaped neighbors, although there was high variability. The water savings of all recognized FFL homes was approximately 35% as compared to their minimally-acceptable turfgrass neighbors. Because of the high variability of the data, however, further analysis is needed to determine the effectiveness of FFL as a water conservation measure.*

Keywords. Irrigation, Turfgrass, Water Conservation, Florida

Introduction

Irrigation is often used to maintain high-quality residential landscapes in Florida and can be a substantial component of a home's total potable water use. Irrigation can account for 59% of total residential potable water use in the United States (Mayer et al. 1999). A study in central Florida found that an annual average of 64% of total potable water use (peaking to 88% in the summer months) was used for irrigation (Haley et al. 2007).

The term xeriscaping, from the Greek word "xeros", meaning dry or arid, was developed by Denver Water in 1981 and has gained popularity in the arid southwest. Several studies have documented the irrigation usage of single-family residential homes that use xeriscaping

(Medina and Lee 2006, Sovocool and Morgan 2005, Medina and Gumper 2004). Most studies documented water savings for all study groups with xeriscape, with Sovocool and Morgan reporting a reduction in total household water demand of 30% in southern Nevada.

While xeriscaping focuses primarily on water conservation, the Florida Friendly Landscaping (FFL) program has a broader environmental scope. The FFL program promotes attractive landscapes and environmentally sustainable practices through nine principles: 1.) right plant, right place, 2.) water efficiently, 3.) fertilize, 4.) mulch, 5.) attract wildlife, 6.) manage yard pests responsibly, 7.) recycle, 8.) reduce storm water runoff, and 9.) protect the waterfront (UF/IFAS 2009a). In the category of water efficiently, the FFL program recommends several water conservation measures such as: grouping plants with similar water needs, reducing irrigation in the summer and winter, and maintaining an automatic rain shutoff device for a sprinkler system (UF/IFAS 2009b). The residential component of FFL is Florida Yards and Neighborhoods (FYN). Homes are recognized as FFL (or FYN) by passing a landscape evaluation.

Unlike xeriscaping in the west, the actual irrigation usage of FFL has not been documented and therefore is not a proven conservation method. The objective of this study was to determine if FFL can be promoted as a water conservation measure based on quantifiable irrigation reduction relative to traditionally-landscaped homes. All FFL-recognized homes that were identified in water billing data from Hillsborough, Pasco, and Pinellas counties in Florida were compared to representative neighbors with acceptable turf quality selected for each FFL home. A subset of FFL homes that were visibly following FFL principles while maintaining an aesthetically pleasing landscape were then compared to their neighbors.

Materials and Methods

Data collection

Tampa Bay Water (TBW), a regional water supply authority, provided monthly billing records for seven member-government service areas: Pasco County, New Port Richey, Pinellas County, St. Petersburg, Northwest Hillsborough County, City of Tampa, and South Central Hillsborough County. Monthly water billing data for over one million customers was provided for the approximate time period of 1998-2010. Water billing data contained total water use (indoor and outdoor combined) for single-family residential properties. Customers did not have separate irrigation meters or have access to reclaimed water. In addition, TBW provided parcel data that included parcel identification numbers and estimates of the green space area. Lists of FFL-recognized homes were provided by Pasco, Pinellas, and Hillsborough counties and generally included at least the address and recognition date.

Identifying FFL homes in billing data

The parcel identification numbers (PIDs) for the 397 FFL homes in Pasco, Pinellas, and Hillsborough counties were obtained from the county property appraiser websites. Of these, 160 were identified in the TBW water billing and parcel data. A home may not have been found in the TBW data if the home is located in a municipality that purchases bulk water from TBW (and thus TBW only has aggregate water consumption for that municipality), the home is a townhome or other non-single-family residential, the home has a private potable well or reuse water, or if there was an error in the address provided.

Site visits of all identified FFL homes were conducted to evaluate the condition of the FFL yard and to identify up to ten nearby homes with acceptable turf quality. Turfgrass quality evaluations were made using the National Turfgrass Evaluation Program (NTEP) procedures (Shearman and Morris, 1998). Ratings of turfgrass quality were based on density, color, and presence of weeds and were on a 1 (dead) to 9 (perfect) scale. The minimum acceptable turf quality for this analysis was 6.

These nearby homes (comparisons) were chosen to be representative of the landscape characteristics of each neighborhood. Approximately 20 of the FFL homes were geographically clustered near at least one other FFL and therefore used the same comparison homes. Using the addresses of the neighbors, PIDs were once again obtained from county property appraiser websites. These PIDs were then used to identify the neighbors in the TBW data.

Data Analysis

All data analysis was performed in SAS. Two excel files were imported into SAS: the list of all FFL homes with recognition dates and the list of PIDs for the FFL homes and neighbors. The TBW water billing and parcel data for each service area were also imported and merged, which yielded over 44 million monthly customer records.

To calculate estimated monthly irrigation use, estimated indoor water use was first calculated using the total water use, estimated average per capita indoor use of 70 gallons/capita/day (based on the Mayer et al. 1999 estimate of 69.3 gpcd), the average household size for member government service areas (ranging from 2.12 to 2.38 people per household), and the irrigated area. The irrigated area used was estimated green space area provided in the parcel datasets and is defined as the lot area minus the sum of the building area and any taxable extra features such as patios. If a monthly billing record for an FFL home was missing, no comparison homes were included for that month. The maximum monthly irrigation depth was set as 15 inches because depths higher than this were deemed excessive for the types of landscapes evaluated for this analysis. Less than 0.6% of irrigation depths were greater than 15 inches.

The FFL and TBW data were merged and 86,511 records were isolated. Because the recognition dates varied from 1995 to 2010, the number of records after recognition for each FFL home and its comparison neighbors varied. A total of 42,621 records after FFL recognition were included in this analysis.

Results and Discussion

The histograms shown below indicate that the majority of customers (FFL and comparison) do not irrigate. Fifty-four percent and 47% of the monthly calculated irrigation depths for FFL and comparison homes, respectively, were 0. The exponential shape of the histograms is consistent with the distribution of all residential irrigators in Hillsborough County, FL observed by Romero and Dukes (2010), and is also consistent with the monthly mean and median calculated irrigation depths. For both FFLs and comparisons, the means exceeded the medians in all months. The median FFL irrigation depth was 0 for nine months out of the year, whereas the median comparison irrigation depth was 0 for two months out of the year.

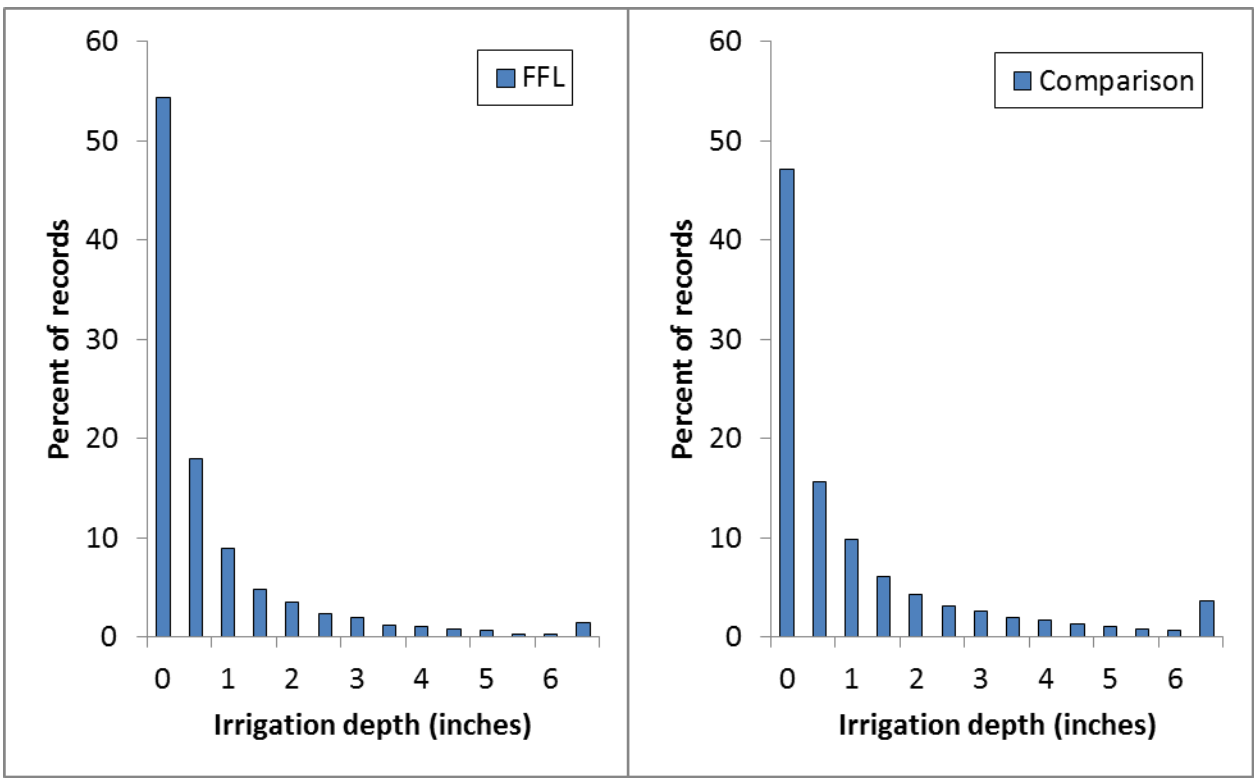

Figure 1. Histograms of calculated monthly irrigation depths over all months of recordfor FFL and comparison homes.

Calculated mean irrigation depths for FFL and comparison homes are shown in Figure 2. The error bars represent standard error. There is a clear trend that FFL uses less irrigation that comparison homes. When modeling the irrigation depth in SAS and controlling for multiple observations for each home and the neighborhood in which homes were located, the mean monthly irrigation was 0.63 inches for FFL and 0.97 inches for comparisons, resulting in a significant ($p<0.0028$) annual water savings of 4.14 inches (35%) for FFL homes.

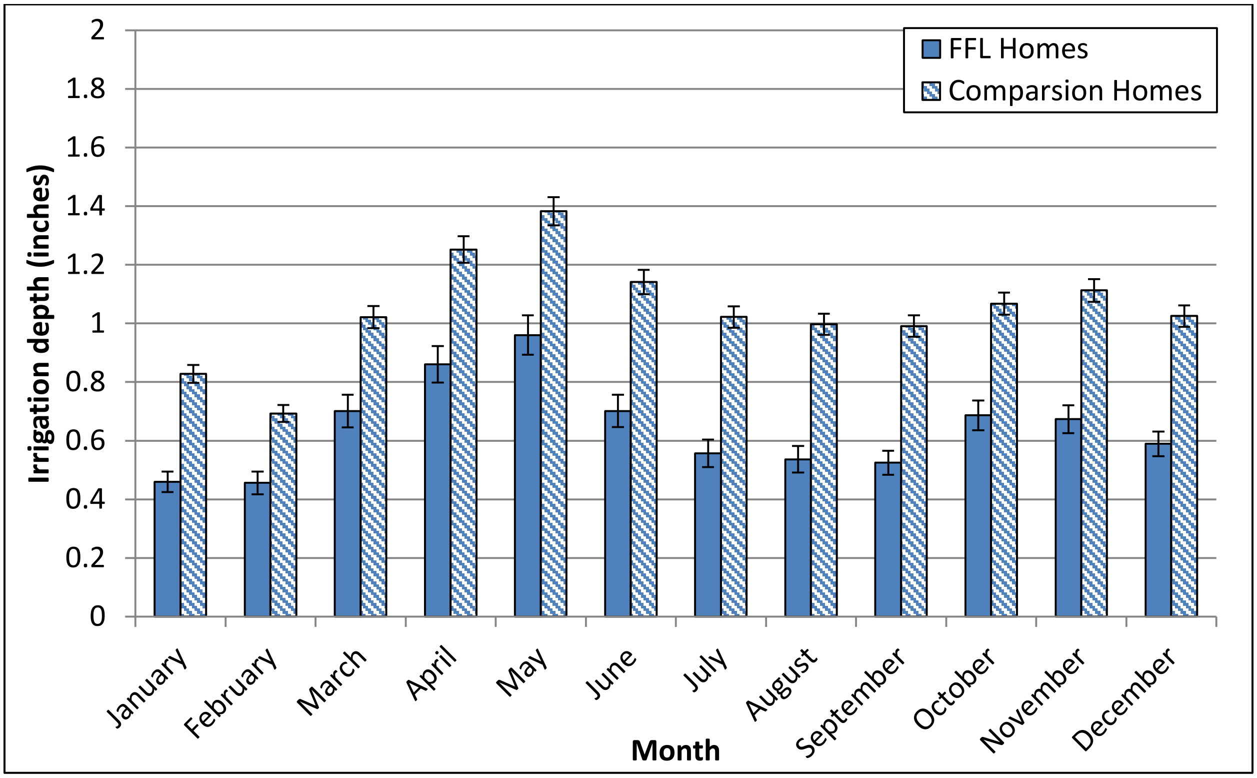

Figure 2. Mean irrigation depths with standard error of all identified FFL homes and their comparisons.

Next, the water savings of good examples of FFL homes were compared to high-quality turf landscapes. Based on the site visits of all FFL homes, it was apparent that there were FFL-recognized homes that were not meeting the intent of the FFL program. These homes may have had landscapes that were not aesthetically pleasing, had poor turf quality, had large gravel landscaped areas, or had very few ornamental areas or plant varieties. Sixty-seven FFL homes were classified as "good examples". Also based on the site visits, it was observed that turf quality tended to vary between neighborhoods and that those homes with high-quality turf (turf quality of 7 or greater) appeared to irrigate more and be better maintained than the minimally acceptable turf landscapes. These higher-quality comparisons would be likely targets for water conservations measures and conversion to FFL.

Results of the good FFL examples and high-quality comparisons are shown in Figure 3 and are similar those shown in Figure 2. There is a clear trend that FFL uses less irrigation that comparison homes. Both the good FFL examples and high-quality comparisons tended to irrigate slightly more. When modeling the irrigation depth in SAS and controlling for multiple observations for each home and the neighborhood in which homes were located, the mean monthly irrigation was 0.63 inches for FFL and 1.13 inches for comparisons, resulting in a significant ($p<0.006$) annual water savings of 5.95 inches (44%) for FFL homes.

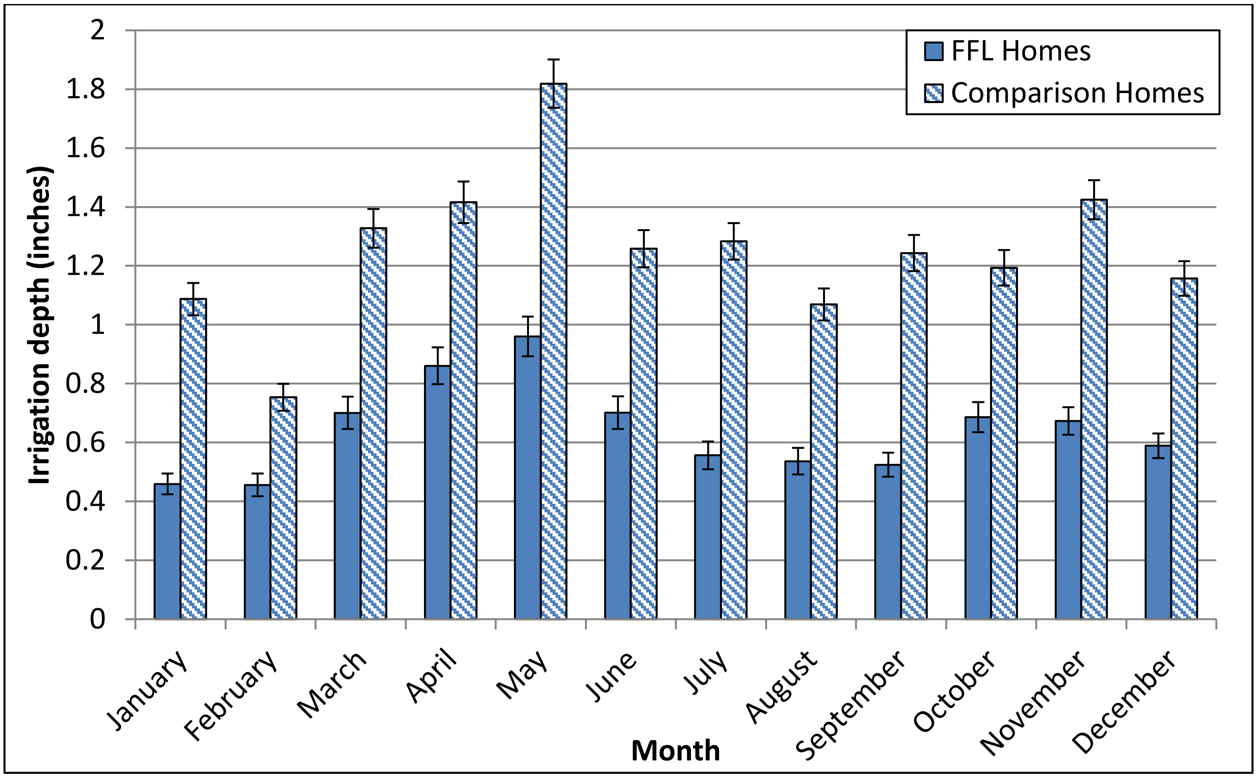

Figure 3. Mean irrigation depths with standard error of all identified FFL homes and their comparisons.

Conclusions

Florida Friendly Landscaped homes tended to irrigate less than their traditionally-landscaped neighbors, although there was high variability. The water savings of all recognized FFL homes was approximately 35% as compared to their minimally-acceptable turfgrass neighbors, and the water savings increased to 44% for good examples of FFL compared to high-quality turfgrass neighbors. Because of the high variability of the data, however, further analysis is needed to determine the effectiveness of FFL as a water conservation measure.

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Soil Moisture Sensors to Reduce Reclaimed Water Irrigation of Landscapes

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Abstract. *Soil moisture sensor systems (SMSs) have demonstrated that they can reduce irrigation application in Florida. However, SMSs have not been tested under Florida soils irrigated with reclaimed water, which contains salts that can affect the measured soil water content. The objective of this research was to assess the potential water savings of different methodologies, including SMS controllers, in homes that use reclaimed water to irrigate their landscapes. Research was conducted in Pinellas County, Florida, in 64 cooperating homes that had pre-existing automated in-ground irrigation system. A dedicated irrigation flowmeter was installed at every participating home. Additional equipment was installed to complete the treatments, as follows: a) 16 homes with a rain sensor, b)16 homes with a rain sensor and educational materials, c) 16 homes with a SMS, and d) 16 homes with no additional equipment (typical for the region), which were monitored only (MO). Preliminary results (16 months) show that homes with SMSs averaged 1.5 irrigation events/week, while all other treatments averaged 2.4—2.9 events/week. Consequently, SMSs was the only treatment that resulted in significant water savings (58%) compared to treatment MO. Turfgrass quality was not significantly different between treatments. This study is expected to continue through 2013.*

Keywords. Reclaimed water, rain sensor, soil moisture sensor, turfgrass quality, water savings.

Introduction

Of the commercially available soil moisture sensor systems (SMSs) for residential use, the most common type is known as an “add-on” device. These SMSs consist of a probe to be inserted in the root zone and a controller to be connected to the time clock, or timer, of an automated irrigation system. On the controller, the user can set a soil water content threshold and, by this means, the SMS will allow or bypass a scheduled irrigation cycle, depending on the soil water content at the programmed start time.

Research performed with these types of SMSs has demonstrated that they can save water under both turfgrass plot conditions (Cardenas-Lailhacar et al., 2008 and 2010; McCready et al., 2009; Grabow et al., 2012) and homeowner settings (Grabow et al., 2010; Haley and Dukes, 2011), while maintaining acceptable turfgrass quality. However, SMSs have not been tested under homeowner conditions where the landscape is irrigated with reclaimed water. This source of irrigation usually contains more salts than potable water. These salts may alter the dielectric permittivity of the soil and, hence, affect the readings of SMSs when measuring the soil water content.

The goal of this on–going research is to evaluate the performance and water conservation potential of a soil moisture sensor system (SMS) in homes that use reclaimed wastewater (RW) as their source for irrigation. Additionally, other water conservation methods that could improve the efficiency of irrigation water application—including rain sensors and educational materials—are being used and compared.

Materials and Methods

To recruit cooperating homes, Pinellas County Utilities (PCU) sent to the University of Florida, Institute of Food and Agricultural Sciences (UF/IFAS) a list of home addresses that were already connected to RW. From that list, UF/IFAS selected five subdivisions in the vicinity of the city of Palm Harbor, Pinellas Co., Florida, and sent letters inviting them to participate in this research project and, if interested, asked them to respond an on-line survey regarding their irrigation systems and practices.

Taking into account the responses to the survey, a total of 98 homes were pre-selected with already installed automated in-ground irrigation systems, connected to RW, and established St. Augustinegrass (*Stenotaphrum secundatum* [Walt.] Kuntze) to limit variability in water use and turfgrass quality across treatment groups. All of these irrigation systems were evaluated at no cost to the homeowners. The objectives of these evaluations were: to check if the homes met the project requirements, to assess if there were some repairs required before the project initiation, to measure the irrigated area, to evaluate which treatment they would be most suitable, and to define the location of any additional equipment.

From the houses visited, 64 were recruited for the study. On every home, a dedicated positive-displacement flowmeter (25.4 mm C-700, Elster AMCO Water, Inc., Ocala, Fla.) was installed to measure the amount of RW used for irrigation. An automatic meter reading (AMR) system (Datamatic, Ltd., Plano, Tex.), which consists of a sensor and a datalogger, was affixed to every installed flowmeter to record, at hourly intervals, the frequency and amount of RW used per irrigation event. Knowing the amount of water applied per irrigation event at each home, as well as their irrigated area, the depth of water applied was then calculated and compared between the different homes and treatments.

The 64 homes selected were split into 4 treatments, with 16 replicates (homes) each, as follows: a) 16 homes with no additional equipment (typical for the region), which were monitored only and used for control/comparison purposes, coded as MO; b) 16 homes with an additional soil moisture sensor system, coded as SMS; c) 16 homes with an additional rain sensor, coded as RS; and d) 16 homes with an additional rain sensor, and where the homeowners received educational materials with instructions on adjusting their irrigation timers seasonally. These materials are customized considering their irrigation system and area under irrigation; coded as EDU. The comparison treatment (MO) did not have any control technology other than the existing timer, common to all homes.

The location of the different rain sensor and soil moisture sensor units was determined in situ, during the irrigation system evaluations. The SMS probes (Acclima/SCX/Digital TDT, Acclima Inc., ID) were buried in a representative zone on each treatment home, following UF/IFAS recommendations (Dukes et al., 2009). The auto-calibration feature of the SMS described in the product's manual was used to set the site-specific thresholds. The wireless RSs (RS-1000, Irritrol Systems Inc., Riverside, CA) were set at a threshold of 6 mm (¼"). The SMS and RS technologies installed correspond to "add-on" devices that were connected to the existing timers. After installing the equipment, project personnel purposefully limited interaction with all cooperators, to obtain results that corresponded to actual homeowner practices.

In addition to water use data collection, turfgrass quality was rated bi-monthly and turf photographs were taken. Initial turfgrass quality ratings were taken for each home during the irrigation evaluations, as a baseline comparison for each home and to estimate potential turfgrass quality decline based on treatments. The turfgrass quality assessment is a subjective process following the National Turfgrass Evaluation Procedures (Shearman and Morris, 1998) based on visual estimates. The rating scale is from 1 to 9, with 1 being poorest or dead and 9 being highest quality possible. A rating of 5 was considered minimally acceptable for home landscapes. The same person conducted turf quality ratings throughout the study.

Partial data reported here were obtained from November 2010 through February 2012. Statistical analyses for irrigation and turfgrass quality data were performed using SAS (2008) with the general linear model procedure (proc GLM) and the mixed model procedure (proc MIXED). Analysis of variance was used to determine treatment effects, and Duncan's multiple range test was used to identify mean treatment differences. Differences were considered significant at a confidence level of 95% or higher ($p \leq 0.05$).

Results and Discussion

Table 1 contains the average irrigation applied per event, the average number of irrigation events per week, the average irrigation depth per week, and the cumulative irrigation for the testing period (November 2010-February 2012) by treatment. It also shows the water savings of treatments RS, EDU, and SMS, compared to treatment MO.

There were no statistical differences in the average depth of water applied per irrigation event between the different treatments during this study (Table 1) and, therefore, differences in water application should be the effect of the different methods/technologies tested to control irrigation. Treatments MO, RS, and EDU recorded significantly more irrigation events per week (between 2.4 and 2.9) than treatment SMS (1.5 irrigation events per week). The number of irrigation events per week for treatments MO, RS, and EDU, agrees with the regular RW restrictions of 3 days per week for Pinellas County Utilities customers (PCU, 2012) during the dry season (April 1 to June 30 and October 1 to November 30). However, this average seems high considering the lower net irrigation requirement during the summer rainy months and the lower evapotranspiration during the two winter seasons tested.

The greater amount of irrigation events per week for treatments MO, RS, and EDU (compared to SMS), resulted in a depth of water applied by these treatments (36 to 43 mm per week) that was significantly higher than treatment SMS (19 mm per week). This last value agrees with the generally recommended single application amount for a sandy soil in Florida (Dukes, 2011).

The cumulative depths of water applied over the 16-month data collection period (Table 1) by treatments MO, RS, and EDU were, again, not different from each other, but significantly different from SMS. This suggests that SMSs can save a significant amount of water compared to the other methods/technologies tested. In this study SMSs saved an average of 58% of the water applied by the homes with no additional irrigation technology other than the irrigation timer (MO). In addition, these water savings did not have a detrimental effect on the turf quality. These results are similar to those found in a study carried out in this same testing area, over a period of 26 months, in homes irrigating with potable water, where SMSs reduced irrigation 65% relative to the comparison group (MO). Similar results were obtained on other studies in Florida, under field plot conditions, where SMS savings averaged 72% during frequent rainfall conditions (Cardenas-Lailhacar et al. 2008) and 54% during dry weather conditions (Cardenas-Lailhacar et al. 2010).

Throughout the 16 months of data collection, no significant differences in average site turfgrass quality ratings were detected among homes based on treatment group (data not shown). In general, turfgrass quality was always above the minimum acceptable (i.e., >5) and, in some cases, even rated as exceptional quality (i.e., 8–9), indicating that irrigation was not restricted in a way that could be detrimental for turfgrass quality.

Conclusions

The SMS treatment was the only group of homes significantly different to the comparison treatment, MO; reducing the average number of irrigation events per week (1.5 vs. 2.9 events/week, respectively), decreasing the depth of the weekly irrigation (19 vs. 43 mm, respectively) and reducing the total cumulative irrigation depth (1091 vs. 2620 mm, respectively). Consequently, SMSs reduced irrigation by 58% compared to the MO group over the 16 months of data collection period. This percent reduction of irrigation water use concurs with those yielded in controlled plot studies and in residential settings using potable water as their irrigation source. Consequently, the amount of salts contained in the RW used for irrigation in this study does not seem to be affecting the SMS readings of the soil water content and, therefore, letting SMSs to adequately bypass unnecessary irrigation events.

These water savings occurred without detriment to the turfgrass quality (which was always above the minimum acceptable rate of 5), and no significant differences in average site turfgrass quality ratings were detected among homes based on treatment group.

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Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the University of Florida and does not imply approval of a product or exclusion of others that may be suitable.

Table 1. Average actual irrigation applied per event, number of irrigation events per week, irrigation depth per week, and cumulative irrigation (November 2010-February 2012) by treatment, and water savings compared to treatment MO.

Treatment[z]	Actual Irrigation				Water savings (%)
	Per event (mm)	Events per week (#)	Per week (mm)	Cumulative (mm)	
MO	15.2 n/s[x]	2.9 a	43 a[y]	2620 a	0
RS	17.0 n/s	2.4 a	40 a	2440 a	7
EDU	14.9 n/s	2.4 a	36 a	2194 a	16
SMS	13.0 n/s	1.5 b	19 b	1091 b	58

[z] Treatments are: MO, timer only; RS, timer plus rain sensor; EDU, timer plus rain sensor plus educational materials; SMS, timer plus soil moisture sensor system.

[y] Different letters within a column indicate statistical difference at $P<0.05$ (Duncan's multiple range test).

[x] n/s = No significant difference .

Two Season Comparison of Nine Smart Controllers

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Abstract. *During the 2011 and 2012 seasons, nine different 'smart' irrigation controllers from various manufacturers were utilized to irrigated 18 similar plots of cool season turfgrass. Each controller serviced two plots, each 30-ft by 30-ft. Four of the controllers were soil moisture based controllers (with a separate sensor installed in each zone) and five were weather based. Each proved successful in maintaining adequate soil moisture for the turfgrass during both seasons, though not without some needed monitoring and adjustment.*

All the controllers were considered appropriate for the small residential or home-owner market. Four of the five soil moisture based controllers were add-on modules, often paired with a basic timer/clock from a different manufacturer. None of the weather based controllers utilized a subscription service for obtaining weather data. Three utilized only on-site temperature sensors to calculate needed irrigation time. Two utilized both air temperature and solar radiation sensors for this purpose.

Every controller had unique strengths and user appeal. The diversity of irrigation strategies and approaches by the various manufacturers ranged from fairly simple and straight forward to more 'black box'. Because the targeted application was for small residential, provided functionality was expectedly not all encompassing. Simple, transparent operation was favored over 'hidden' processes or algorithms that attempted to 'magically' but generically correct for most conditions.

Key functionality and features of the nine controllers are summarized in more detail below, providing basic guidance to consumers in matching their needs and expectations to products currently available in the irrigation industry.

Keywords. Smart irrigation controller, weather based controller, soil moisture based controller, soil moisture sensor.

Procedures

During the 2012 season, nine different 'smart' irrigation controllers from various manufacturers were utilized to irrigated 18 similar plots of cool season turfgrass. Seven of these were also utilized during the 2011 season. Each controller serviced a 30-ft by 30-ft plot of tall fescue (zone 1) and a 30-ft by 30-ft plot of Kentucky bluegrass (zone 2). Four of the controllers were soil moisture based controllers (with a separate sensor installed in each zone) and five were weather based. Tables 1 and 2 provide general information about the plots and controllers.

Plot	Turfgrass	'Smart' controller	Basis of control	Configuration	Sensors
B1-1	Tall fescue	MorpH2O AguaMiser	Soil moisture based	Add-on modules	Wireless soil moisture sensor in plots
B2-1	Kentucky bluegrass				
B1-2	Tall fescue	BaseLine WaterTec S100	Soil moisture based	Add-on modules	Soil moisture sensor in plots
B2-2	Kentucky bluegrass				
B1-3	Tall fescue	Rainbird SMRT-Y	Soil moisture based	Add-on modules	Soil moisture sensor in plots
B2-3	Kentucky bluegrass				
B1-4	Tall fescue	Acclima SC6	Soil moisture based	Sensors connect directly	Soil moisture sensor in plots
B2-4	Kentucky bluegrass				
B1-6	Tall fescue	Aqua Conserve ET-6	Weather based	Plug-in sensor	Air temperature sensor
B2-6	Kentucky bluegrass				
B1-7	Tall fescue	Rainbird ESP-SMT	Weather based	Sensor module incorporated	Air temperature sensor
B2-7	Kentucky bluegrass				
B1-8	Tall fescue	Weather matic SmartLine SL800	Weather based	Plug-in sensor	Air temperature sensor
B2-8	Kentucky bluegrass				
B1-9	Tall fescue	Irritrol Climate Logic	Weather based	Wireless plug-in module	Air temperature & solar sensors
B2-9	Kentucky bluegrass				
B1-10	Tall fescue	Hunter Pro-C Solar-Sync	Weather based	Add-on module	Air temperature & solar sensors
B2-10	Kentucky bluegrass				

Table 1. Summary of 'smart' controllers included in demonstration.

Plot	'Smart' controller			
B1-1 B2-1	MorpH2O AguaMiser	Wireless	Shuts off irrigation at specified threshold.	New in 2012
B1-2 B2-2	BaseLine WaterTec S100	Utilize existing wires to zone valve to connect sensor to interface at controller.	Allows irrigation at specified threshold.	
B1-3 B2-3	Rainbird SMRT-Y	Utilize existing wires to zone valve to connect sensor to interface at controller.	Allows irrigation at specified threshold.	Currently off market
B1-4 B2-4	Acclima SC6	Utilize existing wires to zone valve to connect sensors directly to controller. Sensors can be assigned to control one or more zones. Large display.	Allows irrigation at specified threshold.	
B1-6 B2-6	Aqua Conserve ET-6	Adjusts historical ET based on temperature sensor. Determines needed run-time minutes for specified irrigation days weekly. Accumulates minutes until at least 50% of peak need.	Varies run-time minutes.	Wireless sensor available
B1-7 B2-7	Rainbird ESP-SMT	Adjusts historical ET based on temperature sensor. Abundant operational data available. Includes auto shutoff for rain & low temper-ature. Estimates next irrigation.	Varies watering days or run-time minutes.	Measure rain w/ tipping bucket gauge
B1-8 B2-8	Weather matic SmartLine SL800	Adjusts historical ET based on temperature sensor. Calculates deficit & accumulates at midnight. Includes auto shutoff for rain.	Varies run-time minutes.	
B1-9 B2-9	Irritrol Climate Logic CL100	Adjusts historical ET based on temperature & solar sensors. Includes auto shutoff for rain & low temperature.	Varies run-time minutes.	New in 2012
B1-10 B2-10	Hunter Pro-C Solar-Sync	Adjusts historical ET based on temperature & solar sensors. Easy to install and setup.	Varies run-time minutes.	

Table 2. Summary of key functionality of 'smart' controllers included in demonstration.

Irrigation

All 18 plots were on a deep silty clay soil, with minimal slope. Irrigation flow to each plot was measured automatically by a dedicated DLJ water meter with pulse output (1 count per gallon) connected to a Campbell Scientific data logger (15-minute intervals). An adjacent weather station provided data for calculating reference ET or ETos using the ASCE standardized Penman-Montieth combination equation.

Although all plots were cool season turfgrass, the tall fescue had an effective root zone of 24 inches while the Kentucky bluegrass was only 12 inches. Flat surface grades, modest sprinkler precipitation rates, and reasonable soil intake rates routinely allowed runtimes where 0.75 inches could be applied per cycle with no significant surface runoff.

All tall fescue zones were irrigated with sprinkler rotors on 30 feet square spacing. All Kentucky blue grass zones were irrigated with Toro Precision spray nozzles on 15-feet square spacing. Annual maintenance and service provided distribution uniformities for all zones in the 0.65 to 0.70 range.

Although initial sprinkler precipitation rates were calculated from sprinkler audits, these were adjusted slightly based on the measured gallon through the flow meter and the runtime minutes set on the corresponding controller. This adjustment was expected as water pressures during early morning watering times can vary with additional zones running. The intent was to apply the design or target depth of irrigation as accurately as possible.

Conclusion

Each of the nine 'smart' controllers included in this demonstration proved functional for maintaining adequate soil moisture for cool season turfgrass. All required installation and setup by personnel having a basic understanding of irrigation principles and systems. None were free of the need for nominal monitoring and service.

No controller was expected to perform *optimally* 'out of box', relying solely on general configuration and setup per the instructions provided by the manufacturer (though some were easier than others). From the beginning, it was recognized that the controller was only one component of the irrigation system and its performance would be impacted by other components and operational constraints. Consequently, the ready ability of a controller to be adjusted or fine tuned was considered an essential feature.

References

Evaluation of ET Based “Smart” Controllers During Droughts

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Abstract. *A smart controller testing facility was established by the Irrigation Technology Center at Texas A&M University in College Station in 2008. The objectives were to (1) evaluate smart controller testing methodology and to (2) determine their performance and reliability under Texas conditions from an “end-user” point of view. The “end-user” is considered to be the landscape or irrigation professional (such as the Licensed Irrigator in Texas) installing the controller. This report summaries the performance of nine smart controllers over an eight month growing season in 2011. Controllers were programmed based on a virtual landscape that evaluated controller performance using multiple plant types (flowers, turf, groundcover, small and large shrubs), soil types (sand, loam and clay), root zone depths (3 to 20 inches) and other site specific characteristics. Controllers were divided into 2 categories, those which utilize on-site sensors to calculate or adjust ET or runtimes; and those which ET values are sent via cellular, radio or the internet. Controller performance was compared to total ETo, plant water requirement (ETc) and the weekly irrigation recommendation of the TexasET Network (http://TexasET.tamu.edu). Results so far indicate that controllers using on-site sensors for calculating irrigation water requirements produced lower water requirements and were more often within the irrigation recommendations of the TexasET Network. Significant seasonal differences in controller performance were also found. Results also indicate problems in quantifying effective rainfall, particularly when using a rain sensor. The 2011 results show controller performance during historic drought conditions.*

Keywords. *Landscape Irrigation, Irrigation Scheduling, Smart Controllers, Evapotranspiration, Water Conservation*

Introduction

The term *smart irrigation controller* is commonly used to refer to various types of controllers that have the capability to calculate and implement irrigation schedules automatically and without human intervention. Ideally, smart controllers are designed to use site specific information to produce irrigation schedules that closely match the day-to-day water use of plants and landscapes. In recent years, manufacturers have introduced a new generation of smart controllers which are being promoted for use in both residential and commercial landscape applications.

However, many questions exist about the performance, dependability and water savings benefits of smart controllers. Of particular concern in Texas is the complication imposed by rainfall. Average rainfall in the State varies from 56 inches in the southeast to less than eight inches in the western desert. In much of the State, significant rainfall commonly occurs during the primary landscape irrigation seasons. Some Texas cities and water purveyors are now mandating smart controllers. If these controllers are to become requirements across the state, then it is important that they be evaluated formally under Texas conditions.

Classification of Smart Controllers

Smart controllers may be defined as irrigation system controllers that determine runtimes for individual stations (or “hydrozones”) based on historic or real-time ETo and/or additional site specific data. We classify smart controllers into four (4) types (see Table 1): Historic ET, Sensor-based, ET, and Central Control.

Many controllers use ETo (potential evapotranspiration) as a basis for computing irrigation schedules in combination with a root-zone water balance. Various methods, climatic data and site factors are used to calculate this water balance. The parameters most commonly used include:

- ET (actual plant evapotranspiration)
- Rainfall
- Site properties (soil texture, root zone depth, water holding capacity)
- MAD (managed allowable depletion)

The IA SWAT committee has proposed an equation for calculating this water balance. For more information, see the IA’s website: http://irrigation.org.

Table 1. Classification of smart controllers by the method used to determine plant water requirements in the calculation of runtimes.

Historic ET	Uses historical ET data from data stored in the controller
Sensor-Based	Uses one or more sensors (usually temperature and/or solar radiation) to adjust or to calculate ETo using an approximate method
ET	Real-time ETo (usually determined using a form of the Penman equation) is transmitted to the controller daily. Alternatively, the runtimes are calculated centrally based on ETo and then transmitted to the controller.
On-Site Weather Station (Central Control)	A controller or a computer which is connected to an on-site weather station equipped with senors that record temperature, relative humidity (or dew point temperature) wind speed and solar radiation for use in calculating ETo with a form of the Penman equation.

Materials and Methods

Testing Equipment and Procedures

Two smart controller testing facilities have been established by the ITC at Texas A&M University in College Station: an indoor lab for testing ET-type controllers and an outdoor lab for sensor-based controllers. Basically, the controllers are connected to a data logger which records the start and stop times for each irrigation event and station (or hydrozone). This information is transferred to a database and used to determine total runtime and irrigation volume for each irrigation event.

Smart Controllers

Nine (9) controllers were provided by manufacturers for the Year 2011 evaluations (Table 2). Each controller was assigned an ID for reporting purposes. Table 2 lists each controller's classification, communication method and on-site sensors, as applicable. The controllers were grouped by type for testing purposes

Table 2. The controller name, type, communication method, and sensors attached of the controllers evaluated in this study. All controllers were connected to a rain shut off device unless equipped with a rain gage.

Controller ID	Controller Name	Type	Communication Method	Sensors[1]	Rain Shutoff
A	ET Water	ET	Pager	None	✓
B	Rainbird ET Manager Cartridge	ET	Pager	Tipping Bucket Rain Gauge	
C	Hunter ET System	Sensor Based	None	Tipping Bucket Rain Gauge, Pyranometer, Temperature/ RH	
D	Hunter Solar Sync	Sensor Based	None	Pyranometer	✓
E	Rainbird ESP SMT	Sensor Based	None	Tipping Bucket Rain Gauge, Temperature	
F	Accurate WeatherSet	Sensor Based	None	Pyranometer	✓
G	Weathermatic Smartline	Sensor Based	None	Temperature	✓
H	Toro Intellisense	ET	Pager	None	✓
I	Irritrol Climate Logic	Sensor Based	None	Temperature, Solar Radiation	✓

Smart Controllers

Each controller was assigned six stations, each station representing a virtual landscaped zone (Table 3). These zones are designed to represent the range in site conditions commonly found in Texas, and provide a range in soil conditions designed to evaluate controller performance in shallow and deep root zones (and low/high water holding capacities). Since we do not recommend that schedules be adjusted for the DU (distribution uniformity), the efficiency was set to 100% if allowed by the controller.

Programing the smart controllers according to these virtual landscapes proved to be problematical, as only two controllers (E and H) had programming options to set all the required parameters defining the landscape (see Table 4). It was impossible to see the actual values that two controllers used for each parameter or to determine how closely these followed the values of the virtual landscape.

One example of programming difficulty was entering root zone depth. Four of the nine controllers did not allow the user to enter the root zone depth (soil depth). Another example is entering landscapes plant information. Three of the controllers did not provide the user the ability to see and adjust the actual coefficient (0.6, 0.8, etc) that corresponds to the selected plant material (i.e., fescue, cool season grass, warm season turf, shrubs, etc.).

Thus, we programmed the controllers to match the virtual landscape as closely as was possible. Manufacturers were given the opportunity to review the programming, which two did. Five of the remaining manufacturers provided to us written recommendations/instructions for station programming, and one manufacturer trusted our judgement in controller programming.

Table 3. The Virtual Landscape which is representative of conditions commonly found in Texas.

	Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
Plant Type	Flowers	Turf	Turf	Groundcover	Small Shrubs	Large Shrubs
Plant Coefficient (Kc)	0.8	0.6	0.6	0.5	0.5	0.3
Root Zone Depth (in)	3	4	4	6	12	20
Soil Type	Sand	Loam	Clay	Sand	Loam	Clay
MAD (%)	50	50	50	50	50	50
Adjustment Factor (Af)	1.0	0.8	0.6	0.5	0.7	0.5
Precipitation Rate (in/hr)	0.2	0.85	1.40	0.5	0.35	1.25
Slope (%)	0-1	0-1	0-1	0-1	0-1	0-1

Table 4. The parameters which the end user could set in each controller DIRECTLY identified by the letter "x."

Controller	Soil Type	Root Zone Depth	MAD	Plant Type	Crop Coefficient	Adjustment Factor	Precipitation Rate	Zip Code or Location	Runtime
A	X	X	X	X		X	X	X	
B[1]	-	-	-		X	-	-	X	X
C	X			X	X	X	X		
D[2]	-	-	-		-	-	-	X	X
E	X	X		X	X	X	X		
F[2]				X					X
G	X			X	X	X	X	X	
H	X	X	X	X	X	X	X	X	
I[2]	-	-	-		-	-	-	X	X

[1] Irrigation amount was set based on plant available water
[2] Controller was programmed for runtime and frequency at peak water demand (July).

Testing Period

The controllers were set up and allowed to run from April 11 to May 29, 2011 and from August 8 to November 20, 2011. Controller performance is reported over seasonal periods. For the purposes of this report, seasons are defined as follows:

- Spring: April 11 to May 29 (48 Days),
- Summer: August 8 to September 4 (28 Days),
- Fall: September 5-November 20 (76 Days).

ETo and Recommended Irrigation

ETo was computed from weather parameters measured at the Texas A&M University Golf Course in College Station, TX which is a part of the TexasET Network (http://TexasET.tamu.edu). The weather parameters were measured with a standard agricultural weather station (Campbell Scientific Inc) which records temperature, solar radiation, wind and relative humidity. ETo was computed using the standardized Penman-Monteith method.

TexasET and the Plant Water Requirement Calculator

In this report, smart controller irrigation volumes are compared to the recommendations of the TexasET Network and Website generated using the *Landscape Plant Water Requirement Calculator* (http://TexasET.tamu.edu) based on a weekly water balance. This is the method that is used in the weekly irrigation recommendations generated by TexasET for users that sign-up for automatic emails. The calculation uses the standard equation:

ETc = (ETo x Kc x Af) - Re (Equation 1)

where: ETc = irrigation requirement
ETo = reference evapotranspiration
Kc = crop coefficient
Af = adjustment factor
Re = effective rainfall

Due to the lack of scientifically derived crop coefficients for most landscape plants, we suggest that users classify plants into one of three categories based on their need for or ability to survive with frequent watering, occasional watering and natural rainfall. Suggested crop coefficients for each are shown in Table 5.

In addition to a Plant Coefficient, users have the option of applying an *Adjustment Factor*. This can be used to adjust the crop coefficient for various site specific factors such as microclimates, allowable stress, or desired plant quality. For most home sites, a *Normal Adjustment Factor* (0.6) is recommended in order to promote water conservation, while an adjustment factor of 1.0 is recommended for sports athletic turf. Table 6 gives the adjustment factor in terms of a plant quality factor.

A weekly irrigation recommendation was produced using equation (1) following the methodology discussed above. The Af used are shown in Table 3. Effective rainfall was calculated using the relationships shown in Table 7.

Table 5. Landscape Plant Water Requirements Calculator Coefficients

Plant Coefficients		Example Plant Types
Warm Season Turf	0.6	Bermuda, St Augustine, Buffalo, Zoysia, etc.
Cool Season Turf	0.8	Fescue, Rye, etc.
Frequent Watering	0.8	Annual Flowers
Occasional Watering	0.5	Perennial Flowers, Groundcover, Tender Woody Shrubs and Vines
Natural Rainfall	0.3	Tough Woody Shrubs and Vines and non-fruit Trees

Table 6. Adjustment Factors in terms of "Plant Quality Factors."

Maximum	1.0
High	0.8
Normal	0.6
Low	0.5
Minimum	0.4

Table 7. TexasET Effective Rainfall Calculator

Rainfall Increment	% Effective
0.0" to 0.1"	0%
0.1" to 1.0"	100%
1.0" to 2.0"	67%
Greater than 2"	0%

Irrigation Adequacy Analysis

The purpose of the irrigation adequacy analysis is to identify controllers which over or under irrigate landscapes. An uncertainty in calculating a water balance is effective rainfall, how much of rainfall is credited for use by the plant. Further complicating rainfall is the use and performance of rain shut off devices by smart controllers.

For this study we broadly define irrigation ***adequacy*** as the range between taking 80% credit for all rainfall and taking no credit for rainfall. These limits are defined as:

Extreme Upper Limit = ETo x Kc (eq. 2)
Adequacy Upper Limit = ETo x Kc x Af (eq. 3)
Adequacy Lower Limit = ETo x Kc x Af - Net (80%) Rainfall (eq. 4)
Extreme Lower = ETo x Kc x Af - Total Rainfall (eq. 5)

The adequacy upper limit is defined as the plant water requirement (eq. 3) without rainfall. Irrigation volumes greater than the upper limit are classified as ***excessive***. The adequacy lower limit is defined as the plant water requirements minus Net Rainfall (eq 4). The IA SWAT Protocol defines net rainfall as 80% of rainfall. Irrigation volumes below than the adequacy lower limit are classified as ***inadequate***.

For comparison purposes, extreme limits are defined by taking no credit for rainfall (upper) and total rainfall (lower). These limits are the maximum and minimum possible plant water requirements.

Results

Results from the Year 2011 evaluation periods are summarized in Tables 9, 10 and 11 by season.

TexasET Comparisons

Controller performance during the Spring evaluation period (April 11-May 29, 2011) was generally poor.

Controllers Passing
None

Best Performers
Controller I had five stations that were within TexasET.
Controller A had four stations that were within TexasET.

Poor Performers
Controllers D and I produced irrigation volumes for the flowers zone in excess of ETo.
Controller B produced irrigation volumes in excess of ETc for four stations.
Seven controllers (B, C, D, E, F, G, H) did not produce irrigation volumes for any stations that were within TexasET.

Controller performance during the Summer evaluation period (August 8-September 4, 2011) was better.

Controllers Passing
None

Best Performers
Controller E had five stations that were within TexasET.
Controllers C, G and H had four stations that were within TexasET.

Poor Performers
Controllers D and I produced irrigation volumes in excess of ETo for two stations.
Controller D had six stations that were in excess of ETc.
Controller D did not produce any stations within TexasET.

Controller Performance during the Fall evaluation period (September 5-November 20, 2011) was generally poor.

Controllers Passing

Controller G

<u>Best Performers</u>
Controller B had four stations that were within TexasET.

<u>Poor Performers</u>
Controllers D and I produced irrigation volumes in excess of ETo.
Controllers D, C, E, F, H, and I produced irrigation volumes in excess of ETc.
Controller D had six stations that were in excess of ETc.

Tables 12-14 show the irrigation ***adequacy*** analysis for each station during the three seasonal periods. Irrigation adequacy distribution analysis results are shown in Table 15 over the study period and seasonally in Tables 16-18. Out of a total of 138 stations (all periods combined), 51 stations (37%) had adequate irrigations, 48 stations (35%) excessive irrigation amounts, and 39 stations (28%) irrigated inadequately. Controller performance appeared best during the Fall period with 55% of stations irrigated adequately. Three controllers (C, E and G) irrigated adequately 83% of the time.

Controller Problems

Four controllers experienced problems during the course of the study.

1. Controller A had a capacitor leak during the course of the study. This resulted in the controller software operating but not being able to turn valves on.
2. Controller C had a sensor module failure that was discovered during a routine check of controller status (power), the manufacturer was notified and a replacement was installed.
3. Although programmed and installed correctly, the Controller F failed to operate 4 out of the 6 programmed stations. The controller is currently being analyzed for a possible software or hardware malfunction.
4. Controller H experienced communication problems multiple times throughout the study. Controller alerts (beeping) occurred on at least 2 occasions during the evaluation period. The manufacturer was notified of the problem and a signal amplifier was installed on the controller. However, it was later determined that the problem was a result temporary poor signal service by the signal provider company in the testing area (a bad tower).
5. Controller D had a recall issued in late 2011 due to possible sensor malfunctions. As a result this model was discontinued and will be replaced with a newer for the 2012 year test.

Table 9. April 11- May 29, 2011 Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation.

Controller ID	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	4.97	3.77	2.99	2.11	2.63	2.5
B	9.23	5.65	4.18	2.99	3.83	5.33
C	3.66	2.30	1.10	1.05	1.16	0.55
D	12.11	7.66	6.00	3.84	5.13	2.49
E	5.49	3.12	1.73	1.31	1.67	0
F	5.58	NA	NA	NA	NA	1.87
G	5.26	2.33	1.85	1.29	1.58	0.58
H	4.27	2.39	1.66	1.27	1.53	0.65
I	12.25	3.70	2.69	1.83	2.73	1.30
Total ETo[1]	11.14					
Total Rainfall[2]	2.83					
TexasET Recommendation	7.09	4.00	3.01	2.07	2.92	1.26
Total ETc[3]	8.91	6.68	6.68	5.57	5.57	3.34

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Golf Course, College Station, Texas.
[2] Total Rainfall collected from TexasET Network Weather Station “TAMU Golf Course”
[3] Rainfall and Adjustment Factor not included in this calculation

Table 10. August 8 - September 4, 2011 Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation.

Controller ID	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	NA	NA	NA	NA	NA	NA
B	3.63	2.14	1.59	1.13	1.58	1.58
C	4.74	2.99	1.49	1.23	1.85	0.55
D	12.13	7.14	5.60	3.86	5.16	2.33
E	5.81	3.45	2.18	1.29	2.42	0
F	4.79	NA	NA	NA	NA	1.6
G	4.32	2.32	1.85	1.28	1.57	0.92
H	5.50	3.53	2.44	1.86	2.52	1.09
I	10.28	3.24	2.42	1.66	2.74	1.45
Total ETo[1]	7.05					
Total Rainfall[2]	0.34					
TexasET Recommendation	5.29	3.04	2.19	1.42	2.13	0.82
Total ETc[3]	5.64	4.23	4.23	3.53	3.53	2.12

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Golf Course, College Station, Texas.
[2] Total Rainfall collected from TexasET Network Weather Station “TAMU Golf Course”
[3] Rainfall and Adjustment Factor not included in this calculation

Table 11. September 5 - November 20, 2011 Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation.

Controller ID	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	NA	NA	NA	NA	NA	NA
B	6.05	2.93	2.17	1.55	0.76	0
C	10.13	5.02	3.18	2.36	3.01	1.11
D	23.17	13.01	10.20	6.72	8.99	4.21
E	9.65	5.16	2.91	1.72	2.43	0
F	9.00	NA	NA	NA	NA	3.40
G	7.11	3.11	2.47	1.71	2.10	0.87
H	9.01	5.57	3.85	2.92	3.97	1.71
I	13.00	4.82	4.00	2.08	4.31	1.46
Total ETo[1]	11.12					
Total Rainfall[2]	2.28					
TexasET Recommendation	6.64	3.65	2.56	1.73	2.48	1.04
Total ETc[3]	8.90	6.67	6.67	5.56	5.56	3.34

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Golf Course, College Station, Texas.

[2] Total Rainfall collected from TexasET Network Weather Station "TAMU Golf Course"

[3] Rainfall and Adjustment Factor not included in this calculation

SUMMARY AND CONCLUSIONS

Over the past five years since starting our "end-user" evaluation of smart controllers, we have seen improvement in their performance. However, the communication and software failures that were evident in our field surveys conducted in San Antonio in 2006 (Fipps, 2008) continue to be a problem for some controllers. In the past four years of bench testing, we have seen some reduction in excessive irrigation characteristic of a few controllers.

Our emphasis continues to be an "end-user" evaluation, how controllers preform as installed in the field. The "end-user" is defined as the landscape or irrigation contractor (such as a licensed irrigator in Texas) who installs and programs the controller.

Although the general performance of the controllers has gradually increased over the last four years, we continue to observe controllers irrigating in excess of ETc. Since ETc is defined as the ETo x Kc, it is the largest possible amount of water a plant will need if no rainfall occurs. This year, three controllers consistently irrigated in excess of ETc, even though over five inches of rainfall occurred during the study. The causes of such excessive irrigation volumes are likely due to improper ETo values and/or insufficient accounting for rainfall.

Three (3) controllers were equipped with tipping-bucket rain gauges which measure actual rainfall and six (6) controllers were equipped with rainfall shutoff sensors as required by Texas landscape irrigation regulations. Rainfall shutoff sensors detect the presence of rainfall and interrupt the irrigation event. During the 2011 evaluation period, below average rainfall occurred as the result of a historic drought. The spring period had the most rainfall (2.83 inches), and no major differences in performance observed between controllers using rain gauges and those using rainfall shutoff devices. This is in contrast to the 2010 study during which over 17 inches of rainfall occurred; and controllers using rain gauges applied irrigation amounts much closer to the recommendations of TexasET.

For a controller to pass our test, it would need to meet plant water requirements (TexasET Recommendations) for all six stations. Of the nine (9) controllers tested, none successfully passed the test during all three irrigation season. However, one controller passed for the fall irrigation season. Results over the last three (3) years have consistently shown that the majority of controllers over-irrigate (i.e., apply more water than is reasonably needed).

Generally, controllers with on-site sensors, performed better and more often irrigated closer to the recommendations of the TexasET Network than those controllers which have ET sent to the controller.

Current plans are to continue evaluation of controllers into the 2012 year. For the 2012 study, three controllers will be replaced with newer models to reflect upgrades in software or sensor technology. While water savings shows promise through the use of some smart irrigation controllers, excessive irrigation is still occurring under some landscape scenarios. Continued evaluation and work with the manufacturers is needed to fine tune these controllers even more to achieve as much water savings as possible.

Table 12. Irrigation adequacy during the Spring Period (April 11-May 29, 2011)

Controller	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station6**
A	Inadequate	Adequate	Adequate	Adequate	Adequate	Excessive
B	Excessive	Excessive	Excessive	Excessive	Adequate	Excessive
C	Inadequate	Inadequate	Inadequate	Adequate	Inadequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Inadequate	Adequate	Inadequate	Adequate	Adequate	Adequate
F	Inadequate	NA	NA	NA	NA	Excessive
G	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Adequate
H	Inadequate	Inadequate	Inadequate	Adequate	Inadequate	Adequate
I	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate

Table 13. Irrigation adequacy during the Summer Period (August 8-September 4, 2011)

Controller	**Station 1**	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station6**
A	NA	NA	NA	NA	NA	NA
B	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Excessive
C	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Excessive	Excessive	Inadequate	Inadequate	Adequate	Inadequate
F	Inadequate	NA	NA	NA	NA	Excessive
G	Inadequate	Inadequate	Inadequate	Inadequate	Inadequate	Adequate
H	Adequate	Excessive	Adequate	Excessive	Excessive	Excessive
I	Excessive	Adequate	Adequate	Adequate	Excessive	Excessive

Table 14. Irrigation adequacy during the Fall Period (September 5-November 20, 2011)

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station6
A	NA	NA	NA	NA	NA	NA
B	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Adequate
C	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate
F	Excessive	NA	NA	NA	NA	Excessive
G	Adequate	Inadequate	Adequate	Adequate	Adequate	Adequate
H	Excessive	Excessive	Adequate	Excessive	Excessive	Excessive
I	Excessive	Adequate	Adequate	Adequate	Excessive	Adequate

Table 15. Distribution of Station Adequacy, Inadequacy and Excess during the entire study.

	A[1]	B	C	D	E	F[1]	G	H	I	%
Adequate	4	4	7	0	10	0	9	5	12	37%
Inadequate	1	8	10	0	5	2	9	4	0	28%
Excessive	1	6	1	18	3	4	0	9	6	35%
% Adequate	NA	22%	39%	0%	56%	NA	50%	28%	67%	

[1] Controller A & F Performance based on only 6 stations

Table 16. Distribution of Station Adequacy, Inadequacy and Excess during the spring period.

	A	B	C	D	E	F	G	H	I	%
Adequate	4	1	2	0	4	NA	3	2	5	44%
Inadequate	1	0	4	0	2	NA	3	4	0	29%
Excessive	1	5	0	6	0	NA	0	0	1	27%

% Adequate	67%	17%	33%	0%	67%	NA	50%	33%	83%	

Table 17. Distribution of Station Adequacy, Inadequacy and Excess during the summer period.

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**%**
Adequate	NA	0	0	0	1	NA	1	2	3	17%
Inadequate	NA	5	6	0	3	NA	5	0	0	45%
Excessive	NA	1	0	6	2	NA	0	4	3	38%
% Adequate	NA	0%	0%	0%	17%	NA	17%	33%	50%	

Table 18. Distribution of Station Adequacy, Inadequacy and Excess during the fall period.

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**%**
Adequate	NA	3	5	0	5	NA	5	1	4	55%
Inadequate	NA	3	0	0	0	NA	1	0	0	9%
Excessive	NA	0	1	6	1	NA	0	5	2	36%
% Adequate	NA	50%	83%	0%	83%	NA	83%	17%	67%	

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Invalid Substantiation for the EPA WaterSense® WBIC Program

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***Abstract*.** *There are 40.5 million acres of irrigated turf lawn in the United States making grass more widely irrigated that the eight following irrigated crops combined (Diep, 2011). The U.S. Environmental Protection Agency's (EPA's) WaterSense® program for weather-based irrigation controllers (WBIC) is designed to promote and enhance the market for commercial and residential irrigation controllers that create or modify irrigation schedules based on landscape attributes and real-time weather by labeling efficient irrigation system control technologies. The EPA anticipates, in full consideration of the research studies on weather-based controllers, realizing, on average, at least 15% saving of applied irrigation water after installation of weather-based irrigation controllers (EPA, 2009). This paper asks if the EPA can empirically and reliably infer from the data provided by the research studies cited by the EPA that WBICs save* $\geq 15\%$ *more water than traditional controllers for its nationally, targeted population. A meta-analysis of these studies shows evidence that the data cited by the EPA cannot be generalized for the purpose of providing a reference point for the EPA WaterSense® program and the assumptions of the EPA regarding the potential savings of WBICs are invalid.*

Keywords. weather-based irrigation controllers, EPA WaterSense, water saving assumptions of WBICs

Introduction

The rationale for the development of the WaterSense specification was determined by the assertion of the EPA and others that irrigation demand is the single largest end use of water in the urban sector in California and elsewhere (Mayer P. , DeOreo, Hayden, & Davis, 2009), forecasted to reach 58% by the year 2020 (Hunt, et al., 2001). Moreover, as much as half of this water is wasted due to evaporation, wind, or runoff often caused by improper irrigation system design, installation, maintenance or scheduling (EPA, 2011). The US Environmental Protection Agency's (EPA) WaterSense WBIC program is designed to address irrigation scheduling for residential and light commercial applications by labeling efficient irrigation system control technologies. Over a period of four years the EPA, in collaboration with irrigation controller manufacturers, water utilities, irrigation industry representatives, developed the *WaterSense Specification for Weather-Based Irrigation Controllers*, releasing the final iteration in 2011 (EPA, 2011). Irrigation controllers are to be tested in accordance with the Smart Water Application Technologies™ (SWAT) test protocols for climatologically based controllers utilizing climate data and some form of evapotranspiration data as a basis for scheduling irrigation. The SWAT protocol established the method by which controllers are tested and provides two output measures of performance: irrigation adequacy and irrigation excess. Irrigation adequacy is a measure of how well the plant's consumptive water needs are met and irrigation excess is a measure of water applied in excess of the plant's landscape consumptive needs (EPA, 2011). Required supplementary features are primarily utilitarian.

The foundation for the WBIC specification are the data derived from eleven research studies conducted from 2001-2009 on the efficacy and efficiency of weather-based controllers[1]. The EPA explicitly avers that, "in full consideration of the findings of these (eleven) numerous studies, WaterSense anticipates seeing overall water savings of approximately 15 percent after installation of weather-based irrigation controllers" (EPA, 2011). The EPA does not conduct its own testing or evaluations of weather-based controllers and relies on third party studies.

This study is a contribution to the discourse on water consumption in the urban sector in two linked areas: the need to conduct studies of urban water use using analysis of variance or other quantitative measures to account for variability and make predictions about water conservation devices, and, associated with the call for robust analysis, the need to empirically quantify consumptive use. It is the position of this paper that the effectiveness and efficiency of water conservation devices for landscape irrigation cannot be quantified without directly measuring outdoor water use. EPA WaterSense calculates detailed potential water, energy and cost savings from the performance of WBICs without empirical data to support its inferences. This paper posits that while the preponderant number of studies on WBICs explicitly examine the effectiveness and/or efficacy of weather-based controllers, the implicit objective of these publicly funded projects is to reduce irrigation water in specific service areas. This explains why the majority of projects target the highest water users and, ceteris paribus, why their results are not generalizable. Generalizability is applied by researchers in all quantitative academic settings. Simply put, generalizability is the extension of research findings and conclusions from a study conducted on a sample population to the population at large. The EPA WaterSense WBIC assumes that inference derived from the research studies are generalizable to the population of the United States who are 'candidates' for WBICs or, approximately, 12,825,000 households (EPA, 2009). What makes a study not generalizable for the entire population can be one or more parameters of the research design. In the case of the eleven research studies, the critical parameter that makes generalization not reasonable or probable is

[1] AquaConserve, 2002; Aquacraft, Inc., 2003; Carlos et al, 2001; Devitt, 2008; IRWD, 2001, LADWP, 2004; Mayer, 2009; MWDOC, 2004; Santa Barbara County Water District, 2003; Saving Water Partnership, 2003; University of Arizona, 2006

'selection bias'. Simply put, the samples selected subjects that are not representative of the target population.

Study Approach

The approach of this study is to conduct a meta-analysis of the research studies that serve as the foundation of the EPA WaterSense program with an emphasis on the generalizability of the studies. That is to say, can EPA WaterSense apply the results of the studies to the wider population it serves? The evidence of this analysis shows that the data are not reliable because water quantities were not measured and derived by extrapolative means and that non-probability sampling was used in virtually all studies. As will be shown, researchers engaged in 'judgmental sampling', deliberately selected their populations because of time or monetary limitations, in a minority of cases, or, in the majority of cases, because they were attempting to prove the efficacy of WBICs within a limited population. In no case, did the researchers randomly sample their populations and therefore, the results of their research cannot be used as generalizable to the entire population. This paper does not ascribe any normative values to the studies nor does this paper evaluate the individual studies. Similarly, this paper does not address the details of the specification of the WBICs nor does it address the performance or robustness of the controllers except for illustrative purposes.

The paper is organized as follows: the second section of the paper provides a short narrative summary of each of the studies examining them for reliability and generalizability. Following each narrative is a short review of the salient points for this study; the third part of the paper will present a table of the salient parameters of the studies; the fourth part of the study discusses the assumptions of EPA WaterSense and the calculations that were derived to justify the WaterSense program. The next section concludes that current data cannot serve to justify the WaterSense program for WBICs and recommends a different, more robust, research design that could lead to generalizable results.

The Research Studies

In the 2009 Appendix A of the WaterSense Draft Specification for Weather-Based Irrigation Controllers Supporting Statement the fourth assumption states that "large-scale, long-term studies have shown that on average, weather-based irrigation controllers have the potential to save at least 20 percent of applied irrigation water". (EPA, 2009). In 2011, the anticipation of EPA WaterSense was to estimate water savings of 15 percent, based on the same eleven studies and an additional study of California WBIC programs (Mayer, DeOreo, Hayden, & Davis, 2009).

AquaConserve (2002)

Residential landscape irrigation studies, using Aqua ET Controllers, were established with Denver Water in Denver, Colorado, and two adjacent water districts in Northern California, the City of Sonoma and the Valley of the Moon Water District, during 2001. The data collected from these studies indicated that participants had a total outdoor water savings of 21%, 23% and 28% for Denver Water, City of Sonoma and Valley of the Moon Water District , respectively (Addink & Rodda, 2002). The average water savings per participants in Denver was 21.47%; the average outdoor water savings per participant in Sonoma was 7.37%; and, the Valley of the Moon Water District average outdoor water savings per participants was 25.1%.
Aqua Conserve provided a list of high volume water users interested in the study project to the Sonoma County Water Agency and the Valley of the Moon Water District. Aqua Conserve personnel installed controllers at 27 residential sites in the City of Sonoma and at 10 residential sites in the Valley of the Moon Water District. All controllers were equipped with temperature sensors. Water usage during 2001 was compared to pre-installation historic use for previous two years for Sonoma and for previous five years for Valley of the Moon. If excessive wilting of the grass or brown spots began to appear in the lawns, the users could press a button and add an additional scheduled

watering (Addink & Rodda, 2002). There was substantial variation in the results, some participants had extremely high water savings, some no water savings and even a few had an increase in water usage compared to historic water usage. Some of the variability could be explained, for example, due to abnormally high water use when a participant added sprinklers, improper controller settings, etc. However, not all of the variability could be explained and rather than arbitrarily leaving out some data, the data from all the participants was included in the final result calculation.

While each study reveals significant savings it is important to point out that the manufacturer of the WBIC provided the agencies a list of high volume water users such that sampling of the population was not unbiased and the results, prima fascia, cannot be used to infer results in the general population Second, users were allowed to manipulate their controllers manually if they felt that additional water was necessary and, third, users were allowed to add sprinklers and increase their usage.

Aquacraft, Inc. (2003)

The Aquacraft, 2003, research study consists of ten controllers installed in Colorado of which nine were residential and one commercial. Seven of the participants volunteered for the study and three were selected based on their high water usage. Overall savings averaged about 20%, however, post-installation water usage increased at four of the sites which was explained by researchers as sites where volunteers had historically under-irrigated.

The results appear to be positive but are not generalizable because seven of the ten sites were voluntarily chosen and the remainder were selected because they were high water users. Volunteers for this study may be motivated by their preference for water conservation or to receive a free controller. Participants selected because of their high water use can only generate data that can be generalized for similar high water users.

Aquacraft (2009)

The Aquacraft, Inc. evaluation of California Weather-Based "Smart" controllers was designed to maximize potential water savings so the targeted sample selected for the Northern California portion of the study were historically high outdoor water users who were identified by historic billing data (Mayer, DeOreo, Hayden, & Davis, 2009). In Southern California, the target sample were 'interested and motivated customers' (Mayer, DeOreo, Hayden, & Davis, 2009). This study is quite broad and reflected the efforts of a collaborative group of agencies: California Department of Water Resources; California Urban Water Conservation Council; Metropolitan Water District of Southern California (MWD); the twenty-six member agencies of MWD in southern California; a consortium of six water agencies in northern California; and, the East Bay Municipal Utility District. There were 2,294 sites in this study, 3,112 controllers. There were three distribution methodologies used: rebate and vouchers; exchange programs; and, direct installations. This is a large study and it is helpful to display its data in table form:

It is important to display the three methods of distribution. The 'exchange' category refers to those users who disconnect their old controllers and bring them to a central location where they receive a WBIC. The 'rebate' program consisted of a check or voucher for a minimum of $50/controller. The 'direct install' were high water users solicited by the appropriate water agency.

Table 1: MWD Smart Controller Distribution by Member, Method and Customer Category (Mayer, DeOreo, Hayden, & Davis, 2009)

Agency	Residential			Commercial		Total
	Exchange	Rebate	Direct	Rebate	Direct	

			Install		Install	
Beverly Hills	1				41	42
Burbank	91					91
Calleguas	78			22		100
Central Basin	78			39	17	134
Eastern	3			100		103
Foothill	347	21				368
Glendale	168					168
Inland	286	93				379
Las Virgenes	22		1		45	68
Long Beach	47	32	198		67	344
LADWP	143		430		47	620
Pasadena	74		11	35		120
SDCWA	676	17		150		843
San Fernando	7					7
Santa Monica	61	3	63	2	1	130
Three Valleys	165					165
Torrance	20					20
USGV	167					167
West Basin	2	29			13	44
Western	39		207	52	379	677
TOTAL	2,475	195	910	400	654	4,634

The sample sets of each method of distribution was not random. Customers were either motivated volunteers, paid to switch out the controllers or solicited because they were high water users. It is not possible to generalize the savings based on the data. One can also observe that the water savings occurred for just above one-half the population.

Carlos (2001)

The Carlos experiment in Northern Nevada consists of four treatments: intuitive irrigation, manually ET scheduled irrigation, manually ET scheduled irrigation with management training, and ET satellite controlled irrigation. Preliminary results indicate a potential of 15-30% water savings using satellite technology. Estimates range from 50% to 70% of the total water supply is used for outdoor irrigation during the summer months and unpublished data suggests that in non-drought years residents typically apply anywhere from 2 to 10 times more water for landscape irrigation than is actually needed (Carlos, Miller, Devitt, & Fernandez, 2001). The study is a 4 x 2 factorial experiment with three replications in a completely random management design. The experiment utilizes localized data generated from weather stations to control the duration and frequency of outdoor irrigation. Weather station data are sent to a PC unit cellularly where ET_0 is computed then sent via satellite dish to an orbiting satellite. The satellite then beams the signal down to an irrigation controller individually located at the consumer's place of residence on a weekly basis. The controller opens the irrigation valve and automatically sets the duration and frequency of irrigation based on a preassessed application rate and distribution efficiency of the irrigation system. The 2001 study does not report any results.

The Carlos study is scientifically robust but two issues make its results inappropriate for generalizability to the EPA WaterSense program. First, the scope of the study is limited to the efficacy of satellite technology to manage landscape irrigation water and, second, while the experiment is conducted randomly, each experimental unit consists of similar turf variety and uniform cultural and management practices.

Devitt (2008)

The Devitt study is a mixed landscape experiment conducted on 27 residential sites in Las Vegas to quantify water savings associated with satellite irrigation controllers (Devitt, Carstensen, & Morris, 2008). A mixed landscape irrigation study conducted on 27 residential sites in Las Vegas to quantify water savings associated with satellite irrigation controllers (Devitt, Carstensen, & Morris, 2008). Seventeen sites were equipped with ET satellite irrigation controllers and ten sites were designated as control sites and retrofitted with non ET-based controllers. Results showed that 13 of the 16 ET Based controller sites saved water compared to four of ten of the non ET-based control sites. Statistical difference occurred between the control and ET based group (ET-based =+20% savings) ($p<0.05$)

Results from the study indicated that water savings were not because of deficit irrigations at the expense of the landscape plant material. Approximately 81% of the variation in the total outdoor use could be described by the total turfgrass area at each site. Such results would suggest that turfgrass limitations have merit, if the grass being restricted is tall fescue growing in an arid environment (Devitt, Carstensen, & Morris, 2008). Devitt, et al, assume that in communities such as Las Vegas, the highest percentage of wtaer use occurs in the residential sector (60%), with the majority used outdoors to irrigate lawns and mixed landscapes (70%). Sites were selected based on an extensive evaluation of landscape plant materials, irrigation system performance, homeowner level of interest in participating, and the presence of tall fescue in the front yard. Ten of the sites were designated as controls; five received seasonal irrigation scheduling information and five received no educational information. All received the identical irrigation controller. All homeowners in the control group were provided a two-page flier every three months on landscape water use and irrigation scheduling recommendations and tips. Electronic water meter-reading devices were installed on each residential water meter and irrigation was restricted to the hours between 10:00 PM and 5:00 AM. Water use (meter readings) at all residential sites, was compared with historical data for each site obtained from the local water purveyor. Indoor use was estimated by subtracting outdoor use (10 PM to 5 AM) from the total meter readings. Historical water use was for total water with no separation between indoor and outdoor use. The average water savings for all smart controller sites is reported to be approximately 20%, and individual savings ranged from 61.6% to -68.1% (US Department of the Interior, 2008).

The Devitt sudy was designed to examine the impact of WBICs in mixed landscape and concluded that the landscape plant material was not negatively effected by the ET-based controllers and 81% of the variation in the total outdoor water use could be described by the total turfgrass area at each site. The results, then, are generalizable in conditions where there is a preponderance of tall fescue turfgrass in an arid environment.

IRWD (2001)

The goal (of the research) of the Irvine ET Controller Study was to study as homogenous a group as possible to improve the validity of the findings. To that end, test sites were selected from "Westpark Village", a development located in the city of Irvine, California. Test homes were targeted as per traditional water conservation program guidelines, i.e., top 20% water users. For Westpark Village, residents with average annual consumption exceeding 200 Hundred Cubic Feet (HCF) derived from three years of billing data defined the top 20%. These 509 homes were sent letters requesting study volunteers. Over 130 households volunteered to participate. From these volunteers 40 homes were selected (Hunt, et al., 2001). Three household groups: a test group; a reference group to account for externalities; and, a postcard group (people receiving a postcard as weather changed suggesting the owners adjust their schedules) were selected. All treatment group households were surveyed prior to the retrofits to gauge their irrigation knowledge and practices and to gauge their receptivity and willingness to pay for this technology. Responses to these questions had no effect on determining whether the home was qualified to be in the study. Overall these results indicate both a genuine customer need as well as willingness to pay for convenient, reasonably priced, weather-based irrigation scheduling technologies and services. All test groups were selected from among the top 23% water users in the development. On an absolute basis, when savings were estimated through a statistical comparison of weather-normalized consumption before and after retrofit, WBICs were able to reduce total household water consumption by roughly 37 gallons per household per day, representing a 7% reduction in total household use or a projected 16% reduction in estimated outdoor use (Hunt, et al., 2001). The authors infer that by targeting roughly the top third of homes in terms of water use (approximately 10,000 homes) ET controllers might be expected to save roughly 57 gallons per household per day, a reduction of 10% in total water use or 24% in outdoor use.

The authors conclude that the total potential savings are suggested for illustration purposes only and that the study is not designed to generate widely generalizable inferences

LADWP (2004)

The LADWP weather-based irrigation pilot study was targeted at large multi-family residential (homeowner associations) and small commercial sites (parks, school, office buildings). The study was implemented during 2002 and 2003 (Bamezai, 2004). The authors posit that, to date, several studies have examined the effectiveness of weather-based irrigation controllers in single-family residential settings, but virtually none have systematically examined how these controllers perform in other types of settings with medium to large landscapes. All twenty-five sites in the study were professionally installed and programmed. On 60 of the 83 acres dedicated irrigation meters were installed. To avoid implementation delays, the study did not randomize the assignment of sites to the vendors. Test sites were selected on a first-come, first-served basis. LADWP staff identified potential commercial, industrial, institutional sites with significant landscapes by examining summer-winter usage differentials. They then contacted these sites to inform them about the pilot program, and to solicit participation. It was not an easy sell in spite of participants being insulated from all study expense. 25 sites were retrofitted with WBICs. Participants were steadily recruited and screened for suitability. At the time of selection, careful attention was paid to the general condition of the irrigation system. Sites with irrigation systems in significant disrepair or sites were significant alterations had been made to the landscape in the prior two years were excluded.

The LADWP site cannot be generalized for wider adoption because the sample set was not randomly selected.

MWDOC (2004)

In the summer of 2003, MWDOC was awarded a Proposition 13 non-point-source pollution control grant from the California State Water Resource Control Board to provide funding asistance for the installations of a new irrigation timer technology (Berg, Hedges, & Jakubowski, 2009). The study had two primary objectives: to capture pre- and post-Smart Time installation data for water quality and runoff flow for two neighborhoods; and, evaluate water savings on the same Smart Timers installed in the program. The "Orange County's Weather Based Irrigation Timer Rebate Reimbursement Program" examined water savings for the entire program area by single-family residences, water savings by commercial installations, runoff flow patterns during pre- and post-interventions, and water qualify changes resulting from WBIC installations. In addition, the study examined water savings by season, brand of Smart Time and type of installaer. The program wide savings of single family residences was about 0.7 Hundred Cubic Feet (HCF)/month (about 18.3 gallons/day (gpd) or 0.0045 gpd/sq ft of irrigated area. This estimate is arrived by calculating the total change in water use in cases where water use changed significantly (increased or decreased, $\alpha=0.05$) and averaging the net change by all the Smart Timers (899) that were qualified for evaluation. However, the amount of water saving will increase, according to the authors, to 1.4 HCF/month (35.7 gpd) if the estimates are made by averaging the net water change (significant increase or decrease) by only those Smart Timers (460) that contributed to significant change in water use (Berg, Hedges, & Jakubowski, 2009). Program wide savings in commercial settings averaged 7.6 HCF/month (about 190 gpd; 0.004 gpd/sq ft irrigated area). In 30% water consumption significantly decreased, 11% increased, 60% had no change. The authors identified three distinct trends in the single-family residences retrofitted with Smart Timers. In about 33% of the accounts, the water consumption significantly decreased ($\alpha=0.05$) after installation of Smart timers. In about 18% of the cases the water consumption increased statistically significantly after installation of Smart Timers. In nearly 50% of the accounts water use did not change significantly upon installation of Smart Timers. The selection process for the 500 single family residences in the study area consisted of a marketing campaign of directly-mailed postcards, letters and two weekend of direct door-to-door marketing by Boy and Eagle Scouts. Following the marketing campaigns, the fifty-three interested residents contacted the rebate program, purchased and installed an approved WBIC and then filed a rebate program application with MWDOC. Participation was a bit over 10% of the neighborhood (Kennedy/Jenks Consultants, 2008).

The authors advise that that this study, notwithstanding its extensive production of data, is limited because: the data were not normalized for weather with advanced statistical modeling; the results obtained were not compared to a control set of similar participants; and, the weather data used in the study was found to be inaccurate due to malfunctioning weather equipment such that all data are currently being re-run (Berg, Hedges, & Jakubowski, 2009). The recommendations of the authors for further study include; the need for periodic readjustment (of crop coefficients) due to seasonal changes; proportionate installation of WBICs in various ET zones; and, random population selection. They conclude that proactive early adopters of the WBIC technology do a better job overall of water conservation (Berg, Hedges, & Jakubowski, 2009).

Santa Barbara County Water District (2003)

The Santa Barbara County Water District program involved six agencies (Santa Barbara County Water Agency, City of Santa Barbara, Goleta Water District, City of Lompoc, City of Santa Maria, and, the Vandenberg Village Community Services District). Each agency developed a list of high-water using customers who served as the target audience for the ET Controller Program. Average water use for January and February and average use for July, August and September for the prior three years was determined for each customer. The average amount of landscaping at residential properties in the study area was about one acre and it was estimated that approximately 50 percent of the water used at a residence goes to the landscape. Then these averages were used to create a ratio of the difference between summer and winter to determine highest irrigation use. ET Controller Program brochures and letters from the water purveyor were mailed to the top 100 high water users from these lists for Goleta Water District and City of Santa Barbara and the top 25 for the other three agencies. (Litton, 2003). A marketing campaign and phone campaign to attract the highest users was conducted and participants had to pay $144 for a 3 year service plan up front. Site visits (6 hours per controller) for pre-screened customers were conducted by staff members which included a Customer To Do list which provided information on the required repairs and installer contact information. The WeatherTRAK ET Controller technology was chosen for the ET Controller Program because a study conducted by Irvine Ranch Water District it (sic) provided conclusive evidence that the WeatherTRAK controller supplied accurate irrigation scheduling by automatically creating a weekly irrigation schedule based on 'real time' evapotranspiration (ET) data from local weather stations (Litton, 2003). Preliminary data indicated that customers are reducing their monthly water use by approximately 26%, with a high of 59% savings and a low of 8% savings. The author further noted that using the factory settings for precipitation rates in the WeatherTRAK controller does not result in reliable savings. On average, the WBICs were over watering turf areas and under watered areas with drop systems.

This study is not generalizable because of sample selection, reliance on data from earlier, ungeneralizable studies and the absence of a reliable baseline.

Saving Water Partnership (2003)

The 2002 study was designed to test the savings potential and customer satisfaction of four types of irrigation controller devices: ET controller and sensor; wireless and hardwired rain sensor; ET controller without a rain sensor; and, irrigation scheduling service (Smith, 2003).
Participant selection was based on a customer's potential to save water. Participant selection was based on a customer's potential to save water. The study participants (including controls) used an average of 375 gallons per day during the peak season above their average daily winder use and are considered very high users. This list produced 2,000 names. Half were invited to participate and the other half would be used to select controls. The 20 participants who received the ET controller with a rain sensor realized the greatest water savings because these customers had a high savings potential. In the study area, the potential impact of utilizing the ET controller and sensor are 'great'. In Seattle there are about 315,000 single-family homes and approximately 15-20% have in-ground automatic irrigation systems. If the estimated 7875 customers who have the 44,800 differential and an automatic irrigation system, installed the ET controller with rain sensor, the Saving Water Partnership could potentially save 1.2 million gallons per day (Smith, 2003).

The above study is generalizable to areas with high water usage. There is evidence of a strong correlation between high water use differential and potential water savings. In these conditions a WBIC can be a valuable tool.

University of Arizona (2006)

This is a field study that evaluated water savings resulting from installation of weather and soil moisture based controllers. Data were collected at 27 residential sites in Tucson, Arizona during August 2004 to July 2006. Devices were installed by a landscape professional with support from manufacturer representatives. The participants consisted of volunteers and high water usage was not a selection criteria. Reported average water savings are 25% for the WBIC and 3.2% for a second WBIC and 4.3% for the moisture sensor WBIC. (US Department of the Interior, 2008).

The apparent success of this study can be traced to the selection of voluntary participants. This study contains a small sample size (27 homes) and does not cite independent third-party review as to the methodology uses and the soundness of the conclusions (Dukes, 2012)

Table of Summary of Case Studies

Table 2: Summary of Case Studies

Study	Customer Target	Marketing Strategy	Scope	Comments
AquaConserve (2002)	Manufacturer provided list of high volume water users	Direct, targeted approach whereby manufacturer directly contacts potential customers	37 WBICs	Users allowed to make adjustments
Aquacraft (2003)	7 volunteer subjects 3 selected as high water users	Initial phone calls and follow up if good candidate	10 WBICs	Reported savings of 20%
Aquacraft (2009)	High water users in half study Motivated customers in other half of study	Web, word of mouth, agency letter	2294 sites	Water savings for about one-half of sample
Carlos (2001)	Identical turf and uniform cultural and management practices of users	Unknown	Unknown but random within sample set	Satellite based technology
Devitt (2008)	Uniform landscape planting, presence of fescue, irrigation system, level of interest	Free controllers	27 WBICs	81% of variation due to preponderance of tall fescue grass
IRWD (2001)	Homogenous group: top 20% billing data identified	Letters requesting volunteers	40 WBICs	Authors cite ungeneralizability of study
LADWP (2004)	Large residential (HOAs), commercial, non-random, time constraints, first come-first-served	Solicited	25 WBICs	Installed meters on 60 of 83 acres
MWDOC (2004)	Intensive marketing campaign that, in the final analysis, required customers to contact the agency to participate	Marketing campaign, Boy Scouts, direct mailing, door-to-door campaign	1,222 WBICs	Less than half had significant water savings
Santa Barbara (2003)	Residential customers with highest water users	Letters to top 100 water users	62 WBICs	Customers had to pay $144 service fee
Saving Water Partnership (2003)	Residential customers with highest water use during peak season	Identified by water agency and directly contacted to participate	106 WBICs	About one-half water bills higher after first year

University of Arizona (2006)	Voluntary participants	Landscape professionals and manufacturers representatives identified users	27 WBICs	Tested WBICs of two types and moisture sensor

Assumptions and Calculations

The EPA WaterSense program derives a number of assumptions about the inferences that can be derived from the research studies. The assumptions are categorized under three headings: Potential water savings; Potential energy savings; and, Cost Effectiveness. The energy savings and cost effectiveness predictions rely on data generated from water savings data which are examined below.

1. The first assumption is that average outdoor usage is approximately 58,000 gallons of water annually. This data is based on Table 5.14 of the Residential End Uses of Water (Mayer, DeOreo, & al, 1999). However, the referred Table indicates an average outdoor use of about 84,738 gallons which represents 58% of total usage
2. The second assumption is that 13,500,000 detached single family homes have automatic irrigation systems based on EIA data
3. The third assumption is that 95% of irrigation systems are candidates for replacement. This is also derived from EIA data
4. The final assumption of the Potential Water Savings section identifies a 15 percent savings after installation of a WBIC.

The calculations that are derived from these assumptions are that each home can save 8,700 gallons/year. The correct assessment, based on the 15% assumption is a potential savings of 12,710 which equates to a potential annual water savings of 163 billion gallons of water per year and a net cost savings of almost $600 million per year

The purpose of this exercise is to illustrate the potential savings, and therefore the high value of conducting scientifically robust, valid, reliable and generalizable data. The potential payoff, should empirical results be positively evaluated by third parties, is significant in terms of water, economic pay-off and energy conservation.

Conclusion

The overarching conclusion of this study is that the EPA WaterSense WBIC program requires robust and reliable data to justify the Weather-Based Irrigation labeling program. Evidence has shown that the data embedded in the studies upon which the foundation for the potential water savings is based are not generalizable. Each of the eleven studies that serve as reference points for the EPA WaterSense program do not provide data that can be generalized beyond the local scope of the individual study. The purpose of the research studies is to evaluate an effective device to reduce water consumption in the irrigation sector. The purpose of the studies is not to provide generalizable data that can be used on a national scale. This study is not a critical evaluation of the research studies. This paper stipulates that the data derived from the studies were used in an ex post facto manner by the WPA WaterSense WBIC program. The studies were not funded by the EPA nor were they designed to as generalizable studies for the national population.

Second, it is clear from the evidence that studies of water conservation do not employ metering devices for the purpose of quantifying irrigation consumption in the urban sector. This paper posits that the importance of water conservation, quantified by the potential savings in water, energy and dollars makes it critically important to measure the water we use for each sector. A quantitative study must be reliable, internally and externally valid, parsimonious, important, replicable and generalizable. Nothing else should be acceptable.

The EPA WaterSense WBIC program needs robust and formal studies to determine the effectiveness of weather-based controllers and should re-visit the issue of data reliability and generalizability when promoting the current program.

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Flow Monitoring in Landscape Irrigation Systems

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Abstract. The increased use of smart irrigation controllers - along with incorporation of weather data and soil moisture sensors among other tools - are indicators of an industry trend toward greater use of technology to drive water conservation and overall system performance. As a key element of this trend, flow sensors are becoming more prevalent to measure water usage and to help manage irrigation systems. ET Water Systems, Inc. has deployed many smart irrigation products and tools which incorporate flow sensors, with customers using flow sensors to:

- Measure water usage during scheduled irrigation, manual watering, and other water usage events;
- Identify high flow conditions (e.g. main line break);
- Identify slow leaks;
- Compare current flow on a station to historical flow data to investigate for issues such as broken heads or blocked drippers; and
- Collect data for water budgeting and compliance purposes.

This paper will use real world field data to demonstrate how to get the most out of flow monitoring. Different flow sensor techniques will be reviewed with a discussion of their accuracy, limitations, and how to use them to enhance irrigation management and water conservation programs.

Keywords. Flow sensing. Flow measurement. Flow management. Flow in irrigation. HermitCrab.Hermit Crab HermitCrab flow monitoring. ETwater flow monitoring.ETwater smart. ETwater SmartWorks panel, smart controller, flow monitoring.

Why have flow sensing?

The use of flow sensing systems falls broadly into two categories:

- To monitor water usage: This would be in some form of volumetric measurement such as gallons or acre feet.
- To check the irrigation system for problems such as broken heads or pipe breaks: These types of readings would be in gallons per minute or similar.

Adding a flow sensing system to an older conventional or “clock” type of irrigation controller generally does not make a lot of sense because the flow data and alerts are not sent anywhere in real-time; they have to be viewed and reacted to at the controller. Managers, owners and contractors typically prefer that flow data be delivered digitally to a computer so it can be graphed and manipulated, in addition to responding to alerts or other issues. With the advent of two-way communications systems built into the latest generation of smart controllers, water usage data and potential issues with flow rates can be transmitted in real time to a remote location.

One of the challenges with smart controller technology is that achieving significant water usage reductions - and attaining the related cost savings- are often elusive unless actual water usage at a site is benchmarked and monitored, often incorporating normalizing factors such as relative evapotranspiration rates from one period to the next. A"Smart Controller" is typically meant to reduce water usage and save money, but if users don't measure the before and after water usage they cannot know the full extent of savings. This is where the value of flow sensing and monitoring can be appreciated.

Typical properties of flow in an irrigation system

A typical irrigation system frequently includes a Master valve and numerous station valves. When an irrigation valve is turned on, water flow through the sensor builds to a high value while the air is being expunged from the system and then decreases to a steady state once the pipes of the irrigation system are full and water is being applied to the landscape. Many measurement systems or irrigation controllers require the input of a "fill time" which is the time required to fill the pipes and achieve a steady flow through the system. It is important to note that fill times may vary from station to station depending on the irrigation system design. The fill time is related to the pipe volume between the station valve and the irrigation method (sprinklers, rotors, drip line, etc.) The more sophisticated and easier-to-use controllers use algorithms in the flow measurement system, but such approaches need to be carefully designed and crafted to ensure that consistent measurements are taken every time a station is turned on. The diagram in Figure 1 below illustrates how flow rates can vary over time, especially immediately after water is turned on.

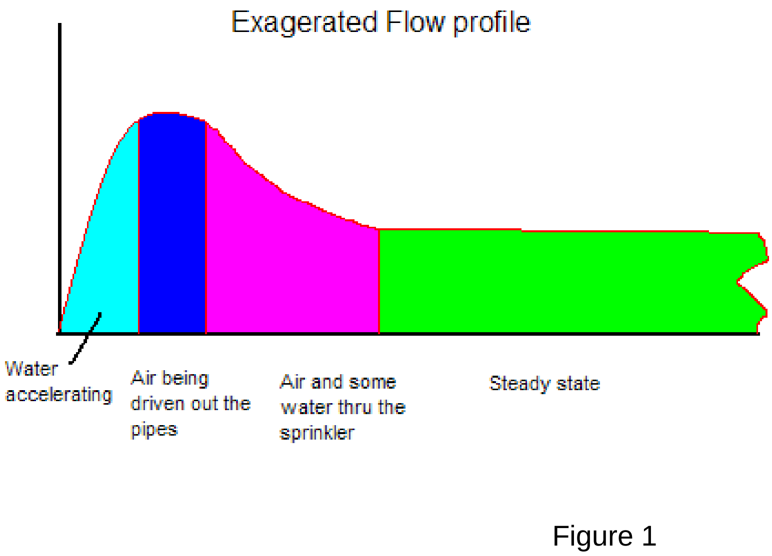


Figure 1

Achieving consistent and accurate flow measurements is important in order to benchmark proper flow rates for a site, with those benchmarks serving as references for accurate and effective high or low flow alerting. False flow alarms are a nuisance that can be avoided once a system is properly benchmarked.

Flow ranges

The amount of flow can vary widely based on several factors. The size of the property and hence the related size of the main irrigation line will make a large difference. Similarly the type of emitter can vary from small low-flow-drip emitters to large-volume rotors.

For this discussion we will review a large residential or small commercial installation capable of 40 gallons per minute (gpm) on a 1 ½ inch mainline. With today's focus on water conservation, drip emitters are used as much as possible. The inherent challenge is the low flow rate of a drip station. In order to determine that a drip emitter is blocked or the restrictive ¼ inch pipe is broken, the flow monitoring system needs to deliver repeatable and consistent readings at low flow volumes. Accuracy would also be desirable, but in this instance repeatability and consistency are the most important factors. The following table indicates some of the flow conditions one might encounter at this site:

	Output	Flow	Comments about requirements
1	Drip emitter	1.2 gpm	Need a consistent low flow measurement capability
2	Large rotors	32 gpm	Largest normal flow on the property
3	Sprays	12 gpm	Small reduction indicates filter clogging. Large increase indicates a head is broken
4	Main line break	Nearly 40 gpm	Need immediate shut down of the master valve

Sensor types

There are many brands and types of flow sensors on the market for measuring the flow of water through pipes. As we focus on the landscape irrigation sector, cost and performance considerations have resulted in two types of flow sensors being used most commonly. They are:

- Paddle type flow sensors.
- Impeller or turbine flow sensors

Other sensor types that are used in the irrigation sector include Ultrasonic, Magnetic and Thermal Mass. In particular, Magnetic type flow sensors are used in very large installations and in some agriculture irrigation systems.

Paddle type flow sensors
A paddle type flow sensor operates when water flowing through the pipe strikes the lower half of the paddle wheel. The upper half is protected from the water flow so the paddle wheel will rotate.
The paddle sensors typically fit into a “T”fitting in the main line as shown in Figure 2 below.

Figure 2

This picture Figure 3 shows the paddle that rotates due to the water flow

Figure 3

The paddle rotation is converted to electrical pulses which are measured or counted to compute the flow reading. Due to stiction (static friction) and other effects, the paddle requires a certain amount of flow before it starts to rotate. Paddle sensors are frequently poor at reading low to very low flows.

Additionally, these types of sensors need a certain length of straight pipe upstream and downstream of their location to minimize turbulence and erroneous readings. The manufacturers typically suggest at least 10 pipe diameters upstream and 5 diameters downstream with no flow disturbances such as valves or bends.

Impeller or turbine flow sensors
There are several manufacturers that market impeller type flow sensors. Typically, these types of flow sensors are integrated into a water meter. Some vendors call these products hydrometers, although a hydrometer is actually a device that measures liquid density and is used in the making of wine or beer. These impeller or turbine flow sensors are incorporated in water meters whose design includes a register that displays water usage. See the following illustration Figure 4.

Figure 4

The picture below Figure 5 shows the internal mechanism of an impeller type flow sensor

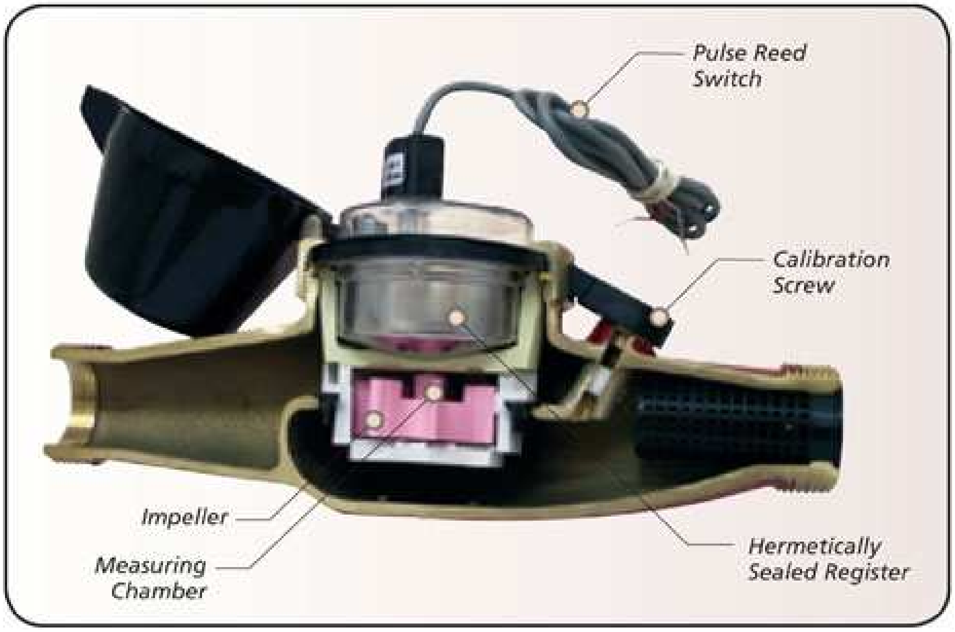


Figure 5

The electrical output from impeller or turbine type flow sensors comes in two varieties: a reed switch with two wires and an optical type sensor with 3 wires. The impellers typically start turning at very low flow rates so flows near 0 can be recorded.

Impeller sensors can also be incorporated into a master valve. Impeller or turbine type flow sensors do not require a straight section of the pipe either upstream or downstream that is clear of flow disturbances.

Which sensor should I use?

The choice of the sensor type depends on a number of factors:

- How is the flow data going to be used by the irrigation contractor or property manager? If, for example, the water usage is going to be compared to water usage reports from utilities or other water purveyors then high accuracy is required;
- Dynamic range of flow that is being measured;
- Cost;
- Ease of installation; and
- User friendliness.

Accuracy and dynamic range

ETwater has tested and worked with a number of flow sensors and found that the specifications provided by manufacturers are often misleading and not always accurate. For example one paddle wheel sensor manufacturer quotes an accuracy of +/- 1% but our tests determined that the accuracy was closer to +/- 3%. Furthermore, the accuracy of the paddle wheel drops off even more dramatically at low flow rates.

The Table 1 below shows the manufacturer-stated performance data for an impeller sensor:

Performance Data

Size	Lowest Flow *within ± 5% Accuracy*	Lowest Flow *within ± 2% Accuracy*	Nominal Flow *within ± 2% Accuracy*	Maximum Flow *within ± 2% Accuracy*
¾"	0.2 GPM	0.9 GPM	11 GPM	14 GPM
1"	0.3 GPM	1.2 GPM	15.4 GPM	20 GPM
1 ½"	0.9 GPM	3.5 GPM	44 GPM	55 GPM

Table 1

This Table 2 below shows the manufacturer-stated performance data for a paddle wheel flow sensor:

FLOW SENSOR MODEL				
NOMINAL SIZE		1 "	1 1/2"	2"
	Feet per Sec	GPM	GPM	GPM
Minimum Flow	0.25	0.86	1.8	2.8
	1	3.5	7.24	11.3
	2	7	14.5	23
	3	10.4	22	34
	5	17	36	57
	7	24	51	79
	10	35	72	113
	12	42	87	136
Maximum Flow	15	52	108	170

Table 2

Note the numbers are a bit misleading and that they are different between the different types of flow sensors. The “Lowest flow” of the impeller type is with a +/- 5% accuracy whereas the “Minimum flow” for the paddle wheel is the minimum it can record. Our tests showed that for a paddle wheel flow sensor the “Minimum flows” indicated in the table were “best case scenarios” of the lowest flow the paddle wheel sensor could register. The impeller type flow sensors, on the other hand, were able to obtain readings well below the “lowest flow” amounts indicated in that table, and in many cases were able to obtain readings all the way down to very nearly 0 flow rates. Based on our test we recommend an impeller type flow sensor when drip systems are used. The paddle wheels often register no flow on a drip system even when there is flow.

Cost

A direct cost comparison is difficult to undertake between paddle wheel flow sensors and impeller flow sensors as the costs, components and specifications can vary widely across type of sensor and type of installation. Much depends on how one specifies and purchases the sensor system. For example, most impeller systems come with a register whereas the paddle wheel sensors do not.

Ease of installation

Some of the differences between types of sensors become particularly clear when it comes to installation. For example, paddle wheel flow sensors require lengths of straight pipe both upstream and downstream of the sensor to eliminate turbulence. This results in many paddle wheel type sensors being installed below grade. Alternatively, the impeller sensor does not have the "straight pipe" requirement and lends itself to installations such as shown in Figure 6, which incorporates an impeller sensor along with a valve and a bend in the pipe in close proximity.

Figure 6

Here the sensor and valve are installed after the back flow preventer. This particular installation is for a transit authority in California. For this user the accuracy of the flow signal was quite important and their choice of flow sensor and type of installation reflected this requirement.

User friendliness

Impeller sensors feature a register which displays the flow that has occurred or is occurring. This provides the user with real-time information that the flow sensor is operating properly, and also allows the local operator to record water usage. An operator can view the register panel which will indicate the level of flow that is occurring. Paddle type sensors operate differently and do not indicate when the paddle is rotating.

ETwater smart irrigation controllers are compatible with many paddle type and impeller type flow sensors. To address the "real-time visibility" issue with many paddle type sensors, all ETwater controllers include an indicator that demonstrates when the flow sensor is pulsing. ETwater controllers also have indicators for solenoid current which provide troubleshooting and diagnostic tools when installing and managing flow sensors of various types. When the user sees a pulsing LED on an ETwater controller, it indicates the sensor is sending flow pulses and the user is then informed that the flow sensor is connected and transmitting flow data.

The picture below, Figure 7 shows some of the LED indicators that ETwater has incorporated in our controllers. This particular unit is an ETwater SmartWorks 50-pin Rain

Bird replacement panel, designed to convert Rain Bird Maxi Com units to ETwater smart irrigation controllers and systems.

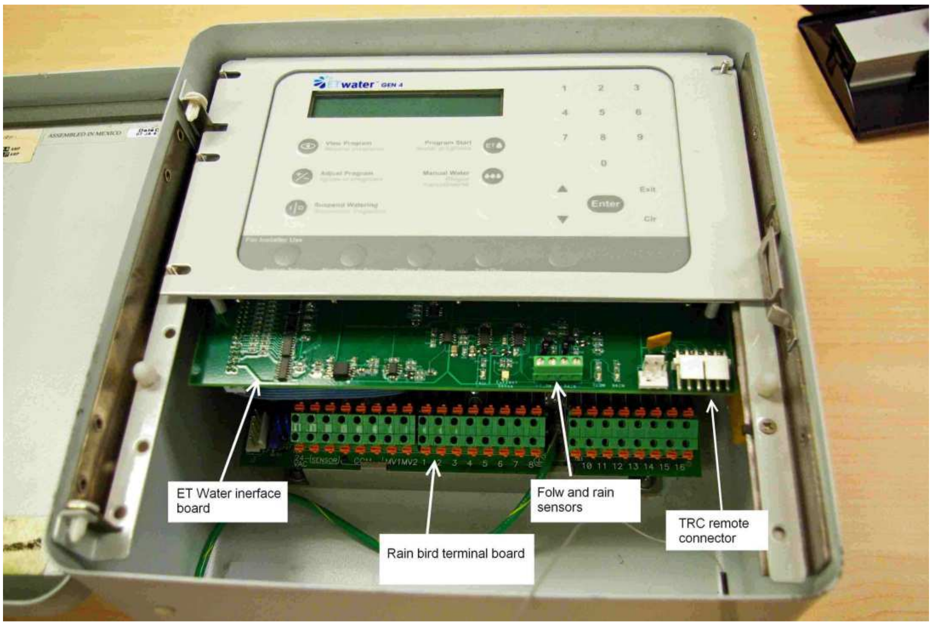


Figure 7

A close up of the LED is shown below in Figure 8

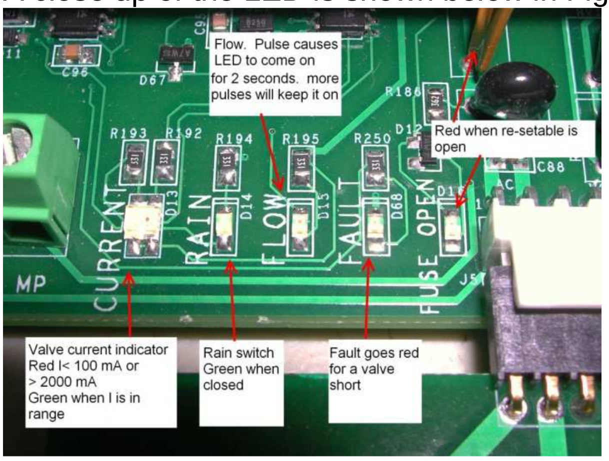


Figure 8

ETwater has recently introduced a flow sensor adapter for its HermitCrab line of retrofit products. The "flow sensor adapter" in the photo below, Figure 9 incorporates easy-to-see LEDs that confirm when the flow sensor is connected and transmitting flow data.

Figure 9

Wired or wireless connections

There has been a lot of industry discussion about and interest in wireless flow sensors. These are particularly attractive for retrofit situations which are already established; as such wireless sensors may alleviate the need to dig a trench for the sensor cable. Several companies are actively marketing wireless sensors. We are intrigued by the possibilities presented by wireless flow sensors, but in our experience their performance has been uneven so far. This may be technology whose time is coming, but has not yet arrived. Examples of issues that we have encountered or about which we have received reports include false readings caused by electrical interference such as from garage doors.

Other efforts to avoid new trenching include work by several companies to put the flow signal on the master valve solenoid control wires or in some sort of 2 wire form.

Sensor wiring

The electrical connections to the flow sensor are amongst the most sensitive on an irrigation controller. Most sensor manufacturers recommend shielded wire of around 18 gauge conductors. Here are a few recommendations based on our experiences with flow sensors:

- Do not use solenoid wires as the sensor wire. They will not be shielded or a twisted pair.

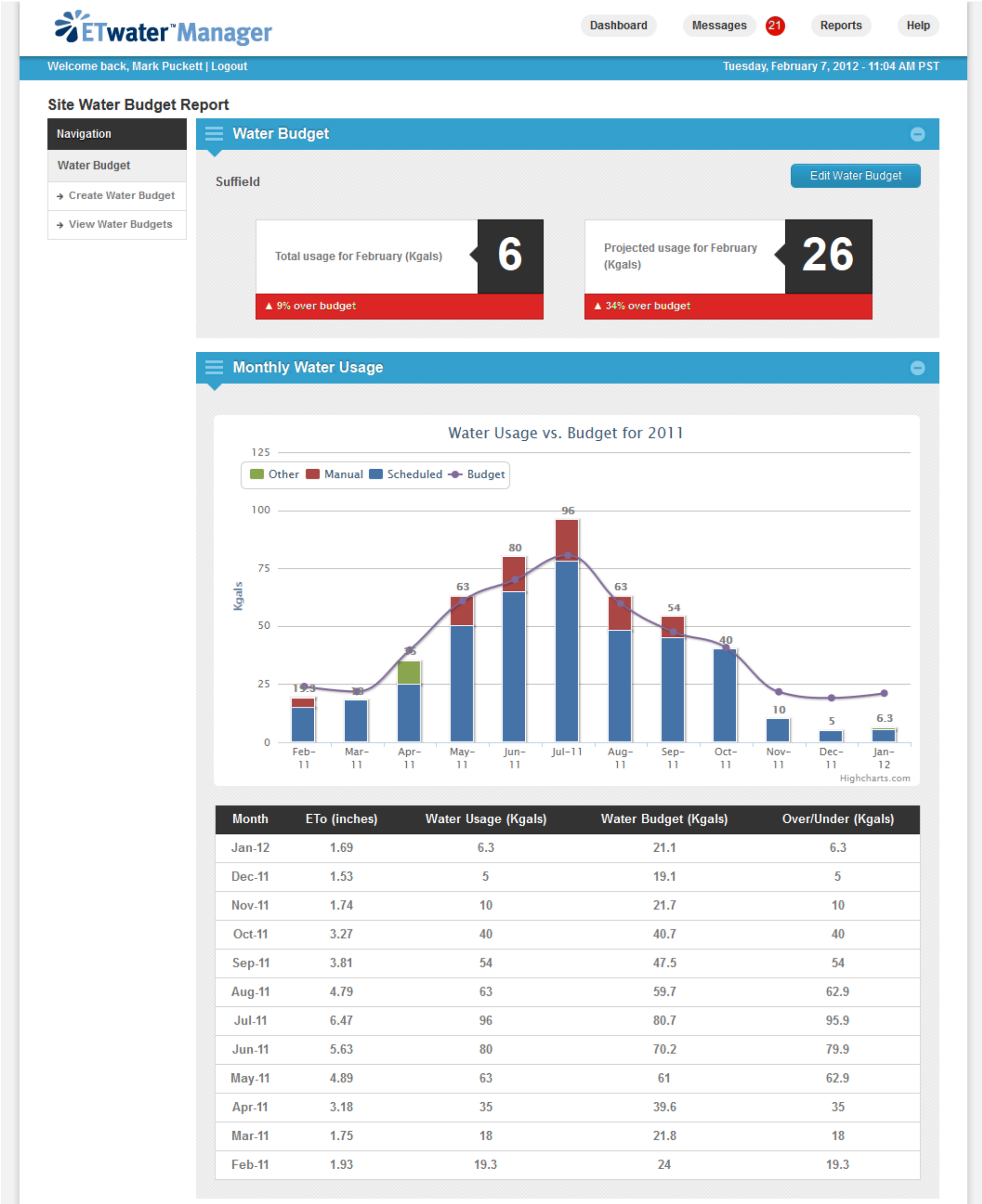
- Avoid running the sensor wires with solenoid wiring if possible. The solenoid wiring can inject noise into the sensor wiring.
- Keep the wiring connections dry. Wet connections will stop the sensor from operating properly.

What to do with the data?

Once the flow sensor data has been collected, it needs to be presented to users in a way that helps identify problems and manage water usage. There are many ways to present data and this topic alone could be the subject of an entire paper. But we will not go into such detail here.

At ETwater we have learned that many users want current flow data to help them manage water usage. To meet these needs ETwater has developed a number of online dashboards and presentation graphics that incorporate flow data, demonstrating historical and budgeted water consumption, along with current readings. ETwater also sends users e-mails in real time based on alerts that are generated by high and low flows.

A representative ETwater display regarding flow is shown in Figure 10 below:



Month	ETo (inches)	Water Usage (Kgals)	Water Budget (Kgals)	Over/Under (Kgals)
Jan-12	1.69	6.3	21.1	6.3
Dec-11	1.53	5	19.1	5
Nov-11	1.74	10	21.7	10
Oct-11	3.27	40	40.7	40
Sep-11	3.81	54	47.5	54
Aug-11	4.79	63	59.7	62.9
Jul-11	6.47	96	80.7	95.9
Jun-11	5.63	80	70.2	79.9
May-11	4.89	63	61	62.9
Apr-11	3.18	35	39.6	35
Mar-11	1.75	18	21.8	18
Feb-11	1.93	19.3	24	19.3

Figure 10

This screen shot shows the current water usage on site versus a water budget. The water budget is developed by the ETwater online tools based on the needs of the landscape, weather, irrigation system, and location.

The user can "drill" into these reports and obtain more detailed information, all the way down to the individual station level. These reports can be run for variable times such as the last 30 days or between dates specified by the user. Below, Figure 11 is part of such a report:

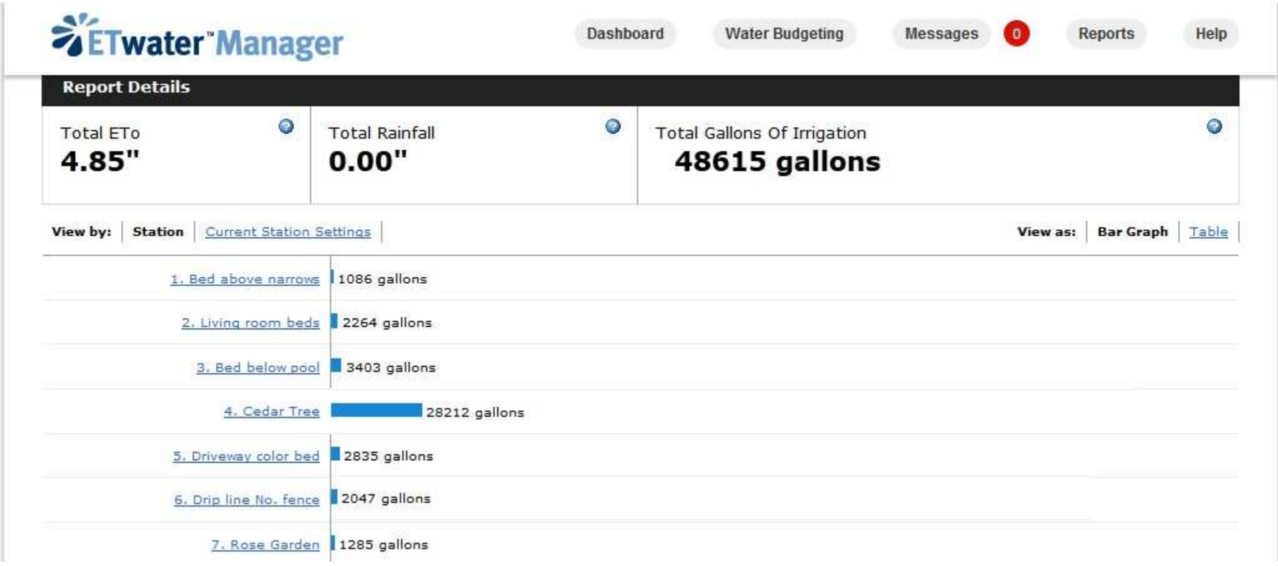
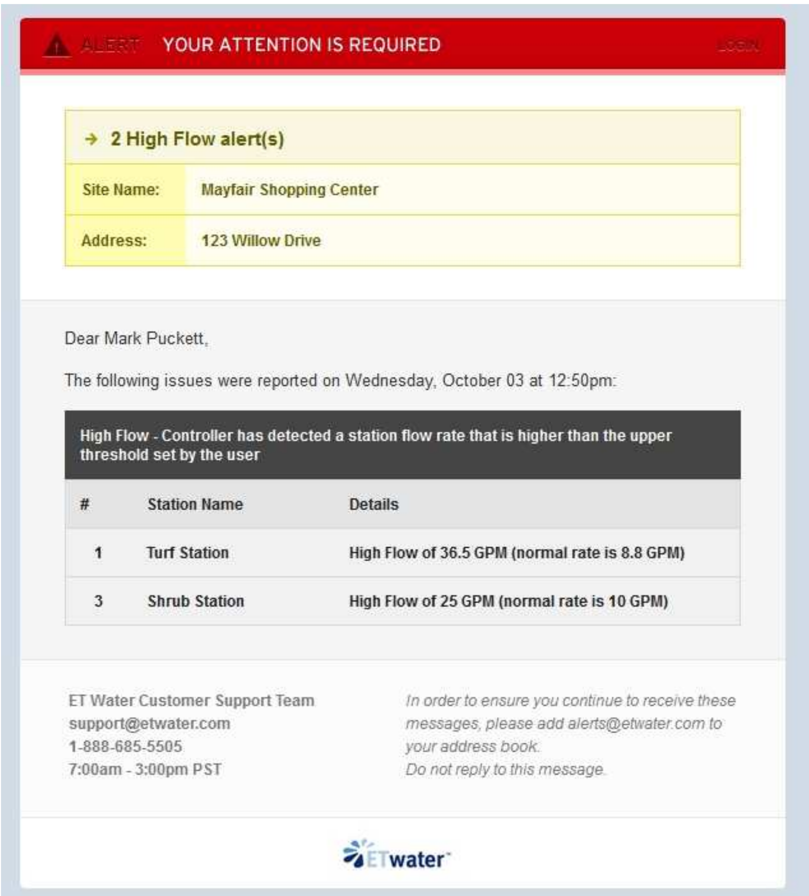


Figure 11

ET Water also provides alert reports showing stations which have generated High or Low Flow alerts. These alerts can be viewed online and are also automatically sent to an email account. Figure 12 is an example email of a high flow alert:



YOUR ATTENTION IS REQUIRED

→ 2 High Flow alert(s)

Site Name:	Mayfair Shopping Center
Address:	123 Willow Drive

Dear Mark Puckett,

The following issues were reported on Wednesday, October 03 at 12:50pm:

High Flow - Controller has detected a station flow rate that is higher than the upper threshold set by the user

#	Station Name	Details
1	Turf Station	High Flow of 36.5 GPM (normal rate is 8.8 GPM)
3	Shrub Station	High Flow of 25 GPM (normal rate is 10 GPM)

ET Water Customer Support Team
support@etwater.com
1-888-685-5505
7:00am - 3:00pm PST

In order to ensure you continue to receive these messages, please add alerts@etwater.com to your address book.
Do not reply to this message.

ETwater

Figure 12

Conclusion

With the push for a reduction in water consumption, along with the costs of water and delivery rising, ETwater is seeing increased demand for flow measurement and the incorporation of flow measurement in managing overall landscape irrigation solutions. Most users of ETwater Smart Irrigation solutionshave installed ETwater systems to save water among other benefits. With that as a backdrop it is natural that many users wish to incorporate flow monitoring to provide greater visibility into system operation and efficiency and greater control and automation in the event of a line break or other system malfunction. The technologies are highly complementary.

In this paper we have identified many of the different technologies that are used for sensing flow. We have discussed the pros and cons of the different leading technologies. And we have demonstrated that flow sensing and smart irrigation solutions can be effectively integrated, as we at ETwater do with all of our solutions now that HermitCrab has been updated to accept flow data.

Flow sensing can help a great deal with the management of the irrigation system and obviously is key to the measurement of water usage. Many flow systems and technologies are relatively new and best practices regarding usage and system integration are not well understood and, in many cases, are still in development. We at ETwater pride ourselves in being able to help and guide our customers in this new area of flow sensing.

Acknowledgements

We would like to acknowledge the following.

Mr. BillBolton in Marin CA for letting us test flow on his site and helping us with copious amounts of data about flow collected over several years.

Manufacturers, Bermad and Netafimand CST for providing samples for us to use in tests.

2Core for providing their latest technology for testing.

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Internet

Types of flow sensors
http://en.wikipedia.org/wiki/Flow_measurement

Making the Right Filter Decisions for Landscape Irrigation

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Abstract. *In today's rapidly changing landscape irrigation environment, water is becoming more scarce, and usage regulations becoming stricter. Providers of domestic, potable water – from public municipalities to private water purveyors – are imposing restrictions to limit the amount of potable water that is used to irrigate the turf and landscaped plantings of commercial properties, golf courses and athletic fields, right-of-ways, and private residences. In many cases, particularly in arid climates where rainfall is scarce, water providers simply do not allow irrigation with potable water.*

As a reaction to this trend, many landscape irrigation systems are turning to alternative sources of water such as private wells, on-site lakes and streams, and captured storm water runoff from roofs, parking lots, and other hardscapes. Additionally, some municipalities are providing pressurized distribution systems of treated wastewater for irrigation use.

The water quality of these untreated alternative sources differs greatly from potable water. Typically, alternative sources contain contaminants such as sand, grit, silt, and algae that can cause damage and wear to the components of a landscape irrigation system. As a result, one of the most important components of these irrigation systems is the filtration used to protect the pump, piping, valves, sprinklers, and drip components from damage and clogging due to the contaminants found in these alternative water sources.

Choosing the right type of filter can be a daunting task, particularly for those whose previous experience had them working exclusively with potable water, and as a result have no prior filtration experience. The following discussion will identify the common types of filtration that are used in landscape irrigation: screen filters, sand media filters, and centrifugal separators. The advantages and disadvantages of each type of filtration will be examined; as well as the criteria to use when selecting the right filter.

Keywords. Landscape, irrigation, filter, filtration, well water, surface water, screen filter, disk filter, sand media filter, centrifugal separator, sand separator, down-hole separator

Typical Irrigation System Issues Caused by Contaminants

When unfiltered water from an alternative source is used in an irrigation system, several problems can present themselves. Large contaminants such as sticks, rocks, coarse sand, and even fish can enter the pump and cause damage to impellers, bearings, and other internal components. When pulling water from a deep well, sand abrasion on the submersible pump can cause the pump to lose its efficiency over time, resulting in a decreased water volume yield, which in turn affects the performance of the irrigation system. Also, wear on a submersible well pump can lead to higher electrical operating costs due to the pump not operating at peak efficiency.

Another common issue caused by unfiltered water is the malfunction and failure of electric control valves. Large particles can become lodged in the area where the valve diaphragm normally seals when the valve is closed, causing the valve to remain open even after the solenoid is deactivated. This is commonly referred to in the irrigation industry as a “stuck valve.” A stuck valve has the potential to waste thousands of gallons of water and cause damage to the landscape; particularly if it goes unnoticed for an extended period of time.

Even if the particles are small enough to pass through the valve diaphragm without becoming lodged, they can still cause abrasion on the diaphragm as they are passed. This abrasion damage prevents the diaphragm from sealing properly when the valve closes, allowing a small amount of water to pass through into the lateral lines. This is commonly referred to as a “weeping” valve. The most common symptom of a weeping valve is large wet areas around each sprinkler head, which may spill out into sidewalks and roadways after a period of time.

Unfiltered water also causes problems with the system’s emission devices – rotor sprinklers, fixed spray sprinklers, microsprays, and driplines. With gear-driven rotor sprinklers, particles can prematurely wear out the gear drives, causing the sprinkler to stop rotating. This is particularly common with the new style of matched precipitation rotary nozzles that many manufacturers have introduced in recent years. Contaminants can cause rotor sprinklers and fixed spray sprinklers to remain in the extended “up” position after the zone is finished watering. This can lead to damage, particularly from mowers and pedestrians.

With all types of emission devices, contaminants can clog the emission orifice, and prevent water from passing. Not only does this risk damage to the landscape due to underwatering, but it can affect the distribution uniformity of the entire station.

Common Contaminants

In order to select the proper filter, an understanding of the common types of contaminants found in alternative water sources must be established. There are two main properties of contaminants that should be taken into consideration when selecting a filter type: **particle size** and **particle weight** (also referred to as specific gravity).

The unit of measure used most often in irrigation to describe the size of a particle is the **micron**. A micron (or more properly, a “micrometer” as it is used in scientific circles) is the equivalent of 1×10^{-6} of a meter, or one-thousandth of one millimeter (.001mm). See Figure 1 below for the micron size of common contaminants found in irrigation water.

Material	Size (Microns)
Coarse Sand	500-1000
Medium Sand	250-500
Fine Sand	100-250
Silt	2-50
Clay	< 2

Figure 1. Source: Irrigation Association, 2000-2002, 2006. Drip Design in the Landscape. Table 8-1, pp. 119.

The weight of the contaminant is another important property to take into consideration. For the purposes of selecting a proper filter, particle weight can be simplified to two categories: **settleable** and **non-settleable**. Settleable particles are heavier than water and will fall to the bottom of a sample jar; while non-settleable particles are lighter than water and will remain suspended in the water. Typically, inorganic substances such as sand, silt, grit, and pipe scale are settleable, while organic contaminants such as algae are non-settleable.

The easiest method to distinguish settleable material from non-settleable is to take a sample of the source water in a jar, shake it up vigorously, and set it down. Any material that settles to the bottom of the jar in approximately three minutes is heavier than water and therefore settleable; any material that remains floating is non-settleable. This simple test is commonly known as the "**Three-minute test**."

Screen Filters

Perhaps the most commonly used filter type in landscape irrigation is the screen filter. Screen filters capture contaminants by providing a physical barrier (the screen) that the water is passed through. The screen element is designed with a particular **mesh size –** the number of holes per linear inch. For example, a 100 mesh screen has 100 holes per liner inch. The larger the mesh size, the finer the screen. Any contaminant larger than the mesh size of the screen will be removed by the filter.

Figure 2. A typical screen filter

In addition to mesh size, "**micron rating**" is another term used to describe the size of a filter's screen. Micron rating is the smallest size particle (in microns) that the filter will remove. It is important to understand both terms and how they relate to one another. Different manufacturers may use different terms, and understanding both is necessary to make adequate comparisons. Figure 3 shows common mesh sizes with their micron rating equivalents. As the mesh size increases, the micron rating gets smaller.

MESH SIZE	MICRON RATING
30 MESH	600 MICRON
60 MESH	250 MICRON
100 MESH	150 MICRON
200 MESH	74 MICRON

Figure 3.

Screen filters are recommended when the amount of contaminants in the water is light to moderate, and the contaminants are both settleable and non-settleable solids. An important aspect to keep in mind when selecting a screen filter for a given application is that the screen will require periodic cleaning and maintenance. As contaminants accumulate on the screen, the pressure loss across the filter increases. It is recommended that the screen element be cleaned when the pressure differential reaches 5-7 psi.

Many types of screen filters require manual disassembly to clean the screen element. Others provide self-cleaning options, such as manual backwashing or automatic cleaning based on pressure differential. It is important to consider the feasible maintenance routines available when selecting a screen filter. If the filter is on an irrigation system in a remote area, it is wise to choose an automatic or easily cleanable filter.

Disk Filters

Another type of barrier filter is the disk filter. Disk filters are very similar to screen filters, but instead of a flat screen element, they have stackable "disks." This creates three-dimensional filtering, and allows buildup of debris on the both the outside of the disks and on the surface area in between the disks.

Figure 4: A typical disk filter element

Disk filters are a good choice for systems that cannot be serviced frequently, as the extra surface area allows more contaminants to accumulate, resulting in longer allowable intervals between cleanings. As with screen filters, disk filters are available with both manual and automatic cleaning options. Again, the expected maintenance routine should be a major factor in deciding whether to install a manual or automatic disk filter.

Selecting the Right Mesh Size for a Screen Filter

There is no “scientific formula” to determine which mesh size is right for a particular application. It can depend on several variables, including the size of the contaminants of the water, the end use of the water (ie. rotor or drip irrigation), and the available maintenance routine.

A general guideline for drip irrigation is to keep the micron rating to $1/10^{th}$ or less of the smallest emission orifice on the drip tubing. For example, if the smallest orifice on a drip tube is 1 mm, the micron rating should be equal to or lower than .1 mm, or 100 microns. For microsprays and microjets, the rule can be expanded to $1/7^{th}$ due to those types of emission devices having a more laminar flow than drip emitters.

Sand Media Filters

Sand media filters are tanks typically constructed from stainless steel or coated carbon steel. The tanks are filled with a fine crushed silica sand, or “media.” Water is pumped into the tank, and downward through the media, where contaminants become caught and are removed from the water. The clean water then flows into a slotted pipe (referred to as an underdrain), where it flows out to the system.

Figure 5: A well pumping water into sand media filters.

Sand media filters are especially advantageous when used in water sources that have a high concentration of organics, such as a stagnant pond or canal, because the three-dimensional filtering process can remove high loads of organics.

The micron rating of sand media filters depends on the size of the media used. The smaller the media, the finer the rate of filtration. Figure 6 shows commonly available media sand sizes and their micron equivalents.

Sand Size	Micron Equivalent
#12	150
#16	105
#20	75

Figure 6.

Sand media filters are cleaned by a process known as backwashing. During a backwash cycle, the normal water flow is reversed and pushed back up through the underdrain. The media bed is fluidized, and suspended contaminants removed. A hydraulically operated valve closes off the inlet to the tank, and the contaminants and backwash water exit through a separate pipe and are piped away to an acceptable discharge point. The flow of the backwash water is regulated by a "throttling valve" on the backwash pipe (typically a standard gate valve) to ensure that just enough flow is available to remove the contaminants and backwash water, but not enough to remove any media. Figure 7 below illustrates the differences between normal operation and a backwash cycle.

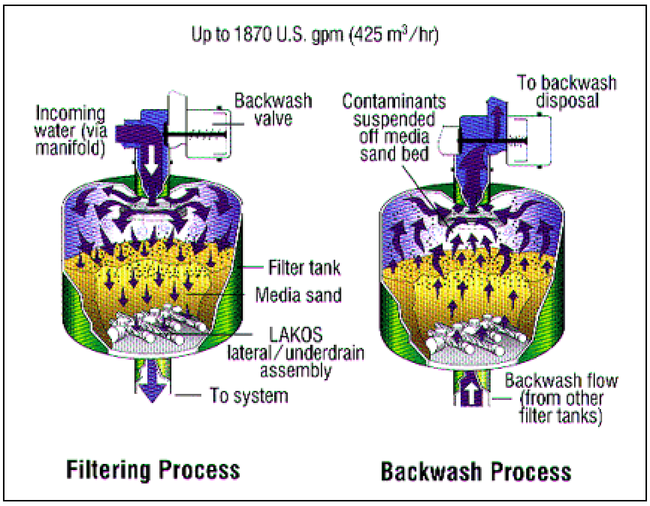

Figure 7.

The backwash process is automated by a controller, and can be triggered based on elapsed time or pressure differential. As with screen filters, it is recommended that media filters be cleaned when the pressure differential across the filter exceeds 5-7 psi.

Although sand media filters are typically seen more in agricultural irrigation, they are a good fit for a landscape irrigation system, especially if the incoming water source is high in suspended organic material.

Centrifugal Separators

When the contaminants in the water are settleable (ie. pass the "three minute test" as discussed previously), often the best filtration choice is a centrifugal separator. Separators employ centrifugal action to separate settleable solids from water. See Figure 8 below for a cutaway drawing showing how a separator works.

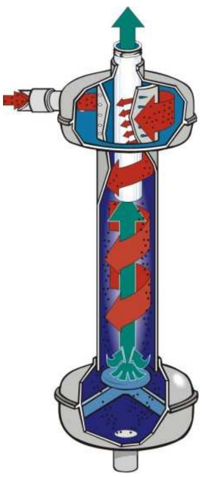

Figure 8.

Water is pumped into the side of the separator's upper chamber and through tangential acceleration slots, which set up a centrifugal action spin. As the water moves in to the middle chamber (known as the "separation barrel"), the particles are influenced by centrifugal action and thrown the perimeter. The particles then gradually lose velocity and fall to the bottom chamber (the "collection" chamber). A vortex forms in the center of the separation barrel, centered on a "spin plate" located just above the collection chamber. This vortex is a low pressure center, similar to the eye of a hurricane, and is the easiest path for the clean water to follow up through the outlet on the very top of the separator. Accumulated particles are then purged periodically from the separator by opening a valve on the bottom "purge exit" of the separator.

Properly designed separators are highly efficient, removing up to 98% of settleable solids 74 micron and larger. Pressure losses are low and steady (typically 3 to 12 psi). Unlike screen filters, which experience an increasing pressure loss as the screen becomes full, a separator will always have the same pressure loss.

The purge of a separator can be automated with an automatic valve for maintenance free operation. This a good option when the system is in a remote location that is not readily accessible for service.

All separators operate within a prescribed flow range that must be adhered to for proper performance. A common misconception is to oversize the separator, or to base the size of the separator on the system pipe size. The separator must have a specific flow in order to achieve the centrifugal action necessary to separate the particles from water.

Pump Intake Filtration

All filters previously discussed are designed to be installed after the pump to protect the irrigation system components. However, it is also critical to use some sort of filtration device on the intake of the pump to protect the pump from damage.

Surface Water Intake Screens

In surface water applications, it is necessary to use an intake screen filter to prevent large particles such as sticks, algae, fish, and other organics from entering the pump and causing damage. The screen is installed in the water at the end of the suction line, below the foot valve.

As with inline screen filters, intake screens are available in a wide variety of mesh sizes. Typically a coarse mesh (10-30 mesh) is used in order to reduce the amount of buildup on the outside of the screen, and therefore reducing maintenance. It should be noted that when a coarse mesh is used, a finer inline filter must be used after the pump to further remove smaller particles before they enter the irrigation system.

There are many different models of intake screens available from various manufacturers. They can range from simple slotted PVC with a nylon mesh covering; to steel self-cleaning models that offer a pressurized backwash line (supplied form the pump) with internal nozzles that rotate the screen to constantly clean the screen and therefore reduce maintenance. Figure 9 below shows an automatic self-cleaning model.

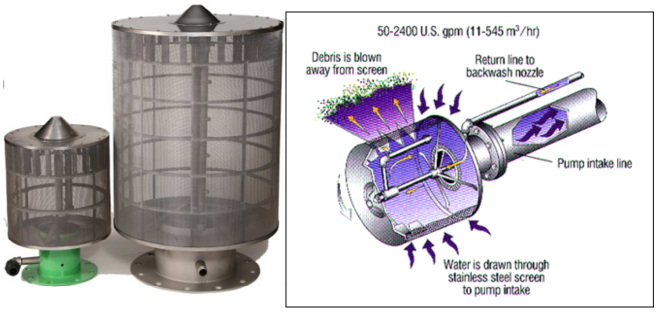

Figure 9.

As with all other filters, the available maintenance routine and budget should be taken into consideration when selecting an intake screen.

Down-hole Separators

If a well pump is suffering damage from heavy abrasive sand particles, a down-hole separator can protect the pump from this abrasive wear. Down-hole separators use the same principle of centrifugal action as above ground separators. The submersible pump is enclosed in a shell, and the separator is attached to the bottom of the shell. The shell acts to isolate the pump intake and force water to enter through the separator before entering the pump.

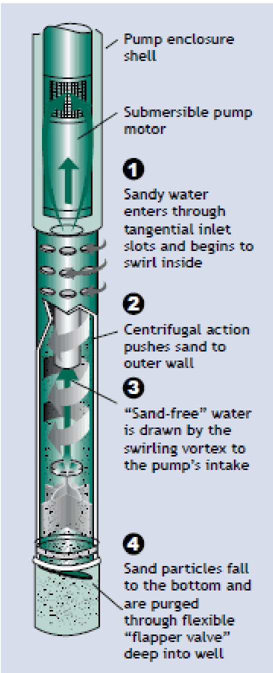

Figure 10. A cutaway diagram of a down-hole separator.

Water is forced into the tangential inlet slots of the separator by head pressure from the well. This sets up the centrifugal action spin which throws the heavy sand to the outer wall, where it loses velocity and falls to the bottom of the separator and accumulates on top of a "flapper valve." A vortex forms in the middle of the separator, and the clean water follows this path up into the enclosure shell and into the pump's intake. When the pump shuts off, the flapper valve opens to discharge accumulated sand deep into the well.

As with above ground separators, down-hole separators depend on operation within a prescribed flow range for optimum performance. In addition to flow rate, several other criteria are required to properly select and install a down-hole separator: The inside diameter of the well casing must be known to ensure the separator will fit into the well. Down-hole separators also require a minimum submergence below the drawdown (pumping) water level to ensure enough head pressure is provided to force the water into the inlet slots. Finally, a certain amount of clearance is required between the bottom of the separator and the bottom of the well to allow for discharged sand to accumulate.

Using a down-hole separator can greatly extend the life of the well pump, and keep it running at optimum yield and efficiency. This can save electrical operating costs over time and maintain optimum irrigation system performance.

A common objection to using down-hole sand separators is the perception that the separator will fill the well up with the discharged sand. It must be noted that the aquifer is not a static body of water, and accumulated sand can leave a well just as easily as it can enter.

Conclusion

One of the most important elements of an irrigation system that draws its water supply from a non-potable source is the filtration. Proper filtration is critical to protect all components of the system: from the pump to the emission devices.

Proper selection of a filter involves taking into account the types of contaminants found in the source water, the frequency and availability of maintenance service to the filter, and the type of emission devices used in the irrigation system.

A properly selected and installed filtration system will protect your irrigation system investment, and ensure its proper operation and performance for years to come.

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Soil Moisture Control of Spray and Subsurface Drip Irrigation: An Analysis of Applied Irrigation, Sensor Placement, and Turf Water Status

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Abstract
A spray-irrigated plot and a subsurface drip irrigated (SDI) plot of tall fescue turf grass were fitted with soil moisture sensors for automated irrigation control. Both plots have dedicated water meters to measure applied irrigation amounts. An adjacent weather station allows calculation of ETos. Sensor placement in the SDI plot (parallel to and equi-distant from adjacent laterals) may have been a factor in subsequent inability to properly control irrigations via soil moisture. Additional soil moisture sensors installed in different configurations in the SDI plot may allow improved irrigation control. Fixed mount infrared temperature sensors and Crop Water Stress Index relationships will allow normalized comparisons of turf water status in the spray and SDI irrigated plots.

Keywords: Sprinkler irrigation, sub-surface drip irrigation, turf, Crop Water Stress Index

Introduction

Subsurface drip irrigation (SDI) in turf is widely viewed as a way to reduce irrigation applications because of the higher efficiencies and uniformities of drip irrigation. Sprinkler irrigation is subject to evaporative losses and distribution effects from wind or system design.

The objective of this project was to determine whether irrigation requirements were less in the subsurface drip irrigated plot than in the sprinkler-irrigated plot. Soil moisture control of irrigation in each plot would provide a plant-based means of determining when and how much irrigation to apply. This technique, however, is dependent on setting the appropriate soil moisture levels and understanding how the soil moisture sensor depth, soil type, and turf rooting depth affect irrigation settings and subsequently, irrigation applications. Therefore, it seemed necessary to introduce an additional independent measure of turf water status. Infrared thermometry has a long history of use in identifying plant water status (Payero et al, 2005; Idso et al., 1981; Jackson et al., 1981; Jackson, 1982). Development of the empirical Crop Water Stress Index (Idso et al, 1981) reduced the data requirements to determine plant water stress. However, the empirical technique comes with its own limitations (Payero et al., 2005). Nonetheless, it is a powerful tool and has been introduced in this project to verify turf water status under the two irrigation systems. Three specific goals of this analysis were to: track irrigations in each plot with comparison to standardized grass reference evapotranspiration (ETos, ASCE-EWRI, 2005), compare soil moistures at the 5 inch soil depth, and track comparative turf water status via the Crop Water Stress Index.

Methods

Tall fescue (*Festuca arundinacea*) was established at Northern Water's headauarters in Berthoud, CO via sprinkler irrigation in each of two adjacent triangular plots in 2006. Plot areas were 1400 sq ft each. Separate valves and flow meters were installed in each plot. The soil type was a Nunn Clay Loam (Fine, smectitic, mesic Aridic Argiustolls). Soil preparation included tillage to 6 inches and amendment with 3 cu yds/1000 sq ft of high quality organic matter.

A pop-up spray irrigation system was installed in one plot. In 2012, distribution uniformity (DU) of the spray system was 0.57. In the other plot, 1/2 inch in-line drip emitter tubing was installed with lines spaced at 15" apart, well within manufacturer guidelines for a clay loam soil. Emitters were spaced at 18 inches and staggered in a triangular pattern. Drip lines were buried at 5 inches.

One 18 inch soil moisture sensor (bi-Sensor, Baseline, Inc, Boise, ID) was installed in each tall fescue plot at the 5 inch depth, slightly deeper than manufacturer's recommendations at the time (Customer Manual, BaseStation 6000, 2006). In the subsurface drip irrigated plot, the sensor was installed parallel to and halfway between the drip lines as per manufacturer's recommendations (Baseline, Inc, 2011).

A lower threshold method was used to set irrigation triggers in the spray plot. Field capacity was 0.35 in/in, while wilting point was considered to be 0.20 in/in. A 50% management allowable depletion (MAD) was set. Cycle and soak settings were employed. The SDI plot, however, was allowed to become drier at the 5 inch soil moisture sensor depth. This decision was based on observations and difficulty keeping similar soil moisture values at the 5 inch depth without over-application on the SDI plot. Applied irrigations were tracked via the flow meters and compared to ETos frequently.

In 2012, Apogee infrared sensors (SI-121, Apogee Instruments, Inc., Logan, UT) were installed in the spray and subsurface drip irrigated plots. Two sensors per plot were installed at a height of 36" and oriented to the east and west at 45 degree angles in each plot. This angle and height kept the field of view well within the plot boundaries. The east-west orientation was intended to minimize support or sensor shadow effects during the middle part of daylight hours. A datalogger (CR850, Campbell Scientific, Inc., Logan, Utah) recorded data on 15 minute intervals. Data from the east and west directions were subsequently averaged in each time segment.

The Apogee thermal data were filtered for post-irrigation, full sunlight conditions on the spray irrigated plot. Data were split and a CWSI baseline developed on half the data. The CWSI was calculated hourly for each plot. CWSI values were used as an independent measure to track the turf water status. The only variables included in this analysis were the turf surface temperature, air temperature, and vapor pressure deficit.

Weather data were obtained from an adjacent weather station at Northern Water's headquarters in Berthoud, CO (http://www.northernwater.org/WaterConservation/WeatherandETData.aspx). Standardized grass reference evapotranspiration (ETos) was calculated from these weather data.

Results and Discussion

Tall fescue is a deep-rooted turfgrass, typically considered to have a rooting depth of 24 inches. The soil moisture sensor placement at 5 inches was not fully indicative of the soil moisture status of the remainder of the rooting zone in either plot, nor of the turf water status. Though the SDI soil moisture was much lower than the spray soil moisture (Figure 1), the SDI CWSI tracked slightly lower than the spray CWSI. This indicated that the SDI tall fescue was accessing soil moisture from deeper in the soil profile than accounted for by the 5 inch depth sensor. Allowing a dry-down in each plot from Day of Year (DOY) 212 to 220 did not increase turf water stress, further indication that the 5 inch depth of soil moisture measurement was not indicative of soil water content in the full tall fescue rooting zone.

The irrigations on the SDI plot tended to over apply (by comparison of applied irrigations to ETos) when it was required to maintain soil moisture closer to field capacity. Past experience after heavy rain has shown that the spray plot can suffer from poor aeration and subsequent stress when soil moisture at 5 inches is near field capacity for several days. It was not considered desirable to allow this condition in the SDI plot. Therefore it was a management decision to allow lower soil moisture at the 5 inch depth in the SDI plot.

The CWSI began declining into negative values in mid-August. Payero et al (2005) documented that inclusion of solar radiation in the CWSI baseline calculation allowed the CWSI to be effectively calculated for times of day other than close to solar noon and for seasonal solar radiation changes. This is likely the reason for the trend in these CWSI values.

Table 1 shows total precipitation plus irrigation (P+I) amounts, ratio of (P+I) to ETos, and total ETos from 7/13/2012-8/20/2012. The SDI P+I amounts were slightly lower than typical turf irrigation recommendations of 0.8*ETo, while the spray irrigation applications were slightly higher than the standard turf irrigation guidelines.

Newer installation guidelines (Baseline, Inc., 2012) suggest installation in the top third of the root zone. Other sources suggest installing sensors at 25% and 60% of rooting depth (Henggeler et al 2011).

Because of logistical difficulties, additional soil moisture sensors were not installed in 2012. Soil moisture sensors will likely be installed at the 60% depth (14 inches) and also at 80% of the 24 inch rooting zone to provide full accounting for soil moisture throughout the profile. These additional measurements will help give better guidance on: soil moisture sensor placement for irrigation scheduling in a deep-rooted turfgrass on a heavy soil, potential drainage through the lower portion of the root zone, and a better understanding of tall fescue soil moisture extraction throughout the soil profile.

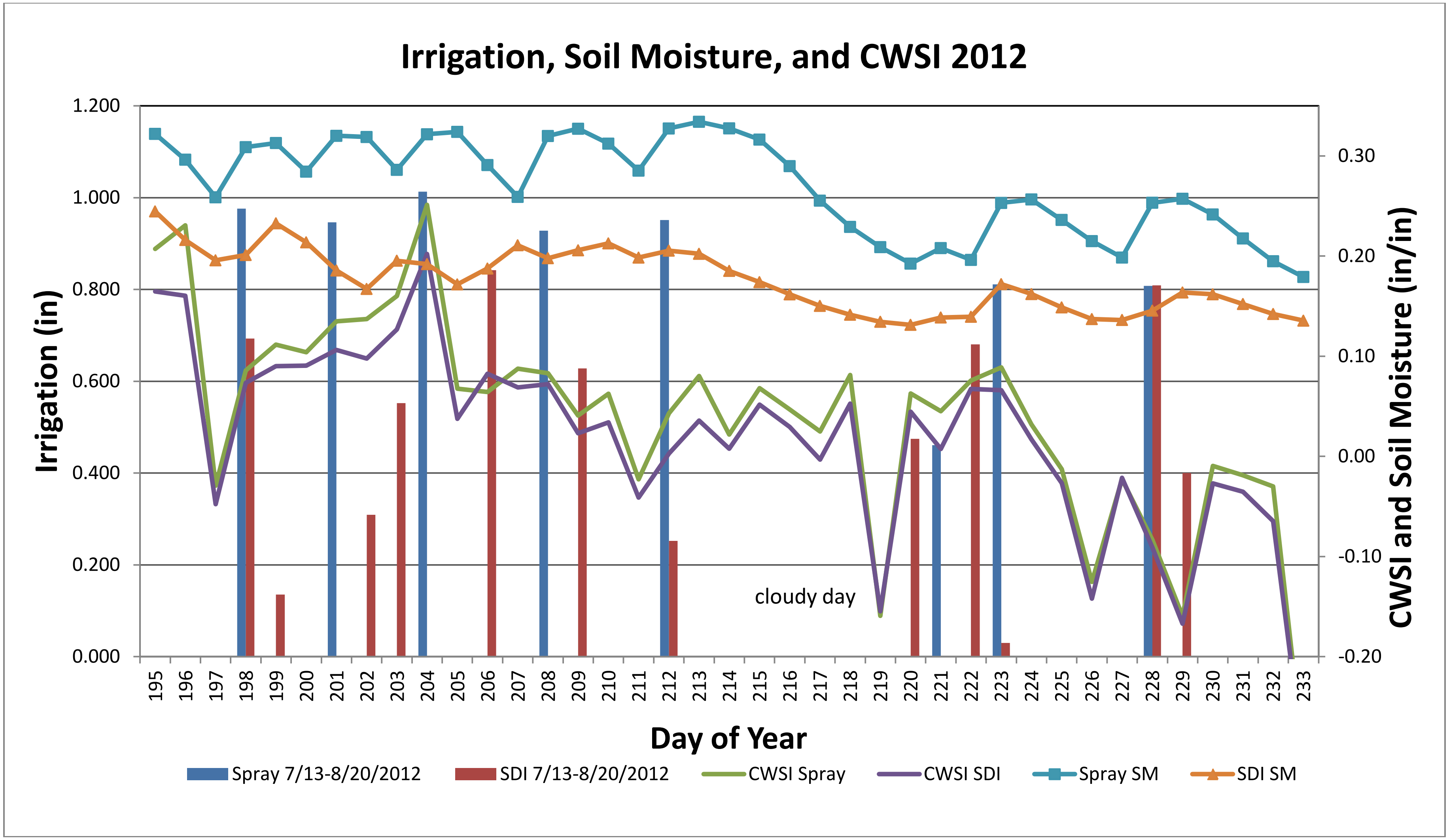

Figure 1. Irrigations, soil moisture, and Crop Water Stress Index for tall fescue from 7/13/2012 to 8/20/2012.

Table 1. Precipitation plus irrigation (P+I) , ratio of P+I to reference ET (ETos), and ETos for the period 7/13/2012-8/20/2012.

7/13-8/20/2012	**Precipitation + Irrigation (in)**	**(P+I)/ETos**	**ETos(in)**
Spray	7.37	0.86	8.61
SDI	6.29	0.73	8.61

Conclusions

The two soil moisture sensors placed as per older recommendations in the tall fescue should be either relocated to deeper depths or supplemented with soil moisture sensors placed at currently recommended depths of 60% of the rooting zone (Henggeler et al., 2011). Placement of soil moisture sensors at the 24 inch depth will provide more complete accounting of soil moisture use and transit in the soil profile.

The CWSI was an independent measure of turf water status. The CWSI in each plot tracked very closely, but irrigation amounts in the SDI plot were considerably less than in the spray plot. Solar radiation will be incorporated into the CWSI baseline calculation to refine the analysis.

These very preliminary results infer that SDI can lead to water savings. This initial year of more intensive effort will lead to some refinements in irrigation practices to optimize performance and standardize procedure.

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Irrigating turf areas with saline and potable water from a subsurface drip system

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Abstract

Research was conducted at New Mexico State University from 2004 to 2012 to investigate the effect of saline and potable water applied from subsurface drip irrigation (SDI) systems on establishment, quality, soil moisture uniformity, and rootzone salinity of warm and cool season turfgrasses. Results for seeded warm season grasses indicate that drip irrigated plots established more slowly than sprinkler irrigated ones but grasses could be successfully established with SDI if seeded early. Irrigation system had no effect on bermudagrass summer or fall turf quality regardless of which fertilizer treatment was applied. Results indicate that warm and cool season grasses can be successfully maintained at acceptable quality over several years in arid regions using subsurface irrigation. Furthermore, the combination of saline water and SDI had no negative effect on warm season grasses or cool season tall fescue.

Subsurface drip irrigation (SDI) systems have been promoted for the use on turf because they irrigate more efficiently as they apply water from emitters placed within the rootzone. Advantages of SDI include the uninterrupted use of the turf area during irrigation, energy savings as a result of lower operating water pressure, no human exposure to irrigation water, reduced disease pressure, and potential water savings because irrigation is limited to the turf area and is not affected by wind drift or evaporation. Arguments against the use of SDI include high installation costs, difficulty in determining spacing and depth of pipes or emitters, a perceived inability to establish turf from seed or sod when using SDI, a perceived interference with regular maintenance, and a perceived inability to leach salts.

Research conducted at New Mexico State University has shown that turf irrigated from a SDI system can be fertilized with granular fertilizer without a loss in color or quality. If sufficient soil water is present, nutrients from the granule will become plant available regardless of whether water is applied from the surface or subsurface. However, most large turf areas with an SDI system have an injection system and apply liquid fertilizer. Home lawns can also be fertilized with a hose-end foliar/liquid fertilization system. If granular pesticide applications require watering-in from the surface either hand watering or a temporary surface irrigation system may have to be used. However, most turf pests can also be controlled by foliar pesticide applications. Core aeration can be applied if the drip lines are installed below the penetration depth of the core aerator. Deep tine aerification cannot be conducted on turf with SDI.

Several research reports have documented that SDI sytems are less effective than sprinkler systems at leaching salts from soils in the absence of adequate rainfall, particularly for rootzone depths above the drip lines. Nonetheless, warm season grasses seashore paspalum, bermudagrass, and inland saltgrass, and cool season tall fescue did not exhibit a decline in summer quality despite salinity fluctuations in the rootzone.

A study investigating soil moisture uniformity on sprinkler and subsurface drip irrigated turf plots revealed that sprinkler irrigation generally resulted in more uniform soil moisture distribution (lower standard deviation values) when compared to drip irrigation. However, the research scenario, perfectly square plots with sprinklers heads placed precisely in each of the 4 corners, is commonly used in turfgrass field experiments, but does not necessarily represent a real-world situation. More research is necessary to investigate if applying water directly to the root zone results in fewer losses and in more efficient irrigation when plots are irregularly shaped, similar to turf areas in a typical landscape.

Salinity Management and Filtration/Treatment of Petroleum Contaminates in Storm Water Catchment Systems for Landscape Irrigation Use

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Abstract: Products and practices used in the management of salinity levels and removing petroleum contaminates that accumulate in storm water catchment systems which may have detrimental effects on turf and plant growth are presented in this paper with a review of several irrigation projects installed in the United States northern climates. How run-off water that contains ice-melt products, hydrocarbons and other contaminates are prevented from entering the irrigation water supply are revealed this paper. Projects such as a large public park and recreation area bordering the coastline and commercial sites that utilize parking lot and roof top run-off are cited as examples. The value of this paper will be that the reader will have a more comprehensive understanding of the water quality issues that are pertinent and unique to storm water catchment systems including identifying the contaminates and how they adversely affect plant growth as well as methods to remove or treat contaminates.

Stormwater For Irrigation Use Overview and Brief History

Stormwater catchment systems for irrigation use have been in practice by farmers for centuries. The simplest systems utilize trenches or catch basins with piping systems to channel water to retention ponds or holding tanks and cisterns. Water quality issues that affect crop production may include pesticides and herbicides introduced to the soil by the farmers and excess salinity from soils breaking down from repeated applications of irrigation water. Filtration of irrigation water in these systems usually only required screens for removing debris that would obstruct distribution flow and perhaps filters that would capture and remove finer particles of sediment and sand from the water supply.
Rainwater harvesting for landscape irrigation use has grown at a phenomenal rate within the last 4 decades since the passing of the USEPA Clean Water Act in 1972 which the Environmental Protection Agency mandates and enforces water quality guidelines as a condition for consideration in construction practices in residential, commercial and municipal development. Along with the Clean Water Act, The National Pollutant Discharge Elimination System (NPDES) authorizes most states to implement the Stormwater NPDES permitting program in which the EPA is the permitting authority and Construction Site Managers are required to obtain these permits prior to the start of construction. More recently, the US Green Building Councils' (www.usgbc.org) Leadership in Energy and Environmental Design (LEED) program which incorporates Water Efficiency (WE) as a category with a potential 11 points of the 110 points available for LEED certification and irrigation WE credits which can account for 10% of the total WE points. Rainwater harvesting systems figure prominently in helping attain LEED credits in landscape irrigation system designs.

Primary rainwater collection sources for landscape irrigation use are roof-top rainwater and storm water run-off collected from impervious surfaces such as sidewalks and parking lots as

well as permeable “hardscape” products used to help minimize storm water from reaching municipal sewer treatment systems.
The demand for bringing the most efficient rain water harvesting systems to market has resulted in the creation of hundreds of companies designing and producing the components necessary for maximizing the efficiency and versatility of these systems. As the demand for rainwater collection systems increases particularly in areas of rapid residential and commercial development, the quality of the water captured may often be overlooked or not given due consideration as to whether it contains elements or contaminants that may prove detrimental to landscape plants and turf.

Potential Water Quality Issues

Developing new building sites or renovating existing buildings that will be incorporating rainwater catchment systems offer a plethora of potential contaminants that may require various methods of treatment prior to application to the landscape.
Most rainwater harvesting systems incorporate products from multiple manufacturers and the filtering components may include:

- catch basins, gutters and drains with screens to prevent the bulkiest of materials from entering the collection system piping
- initial or pre-filtration devices to remove additional debris, sediment and other non-biodegradable materials from the water supply
- a submersible pump with an intake screen mounted on a sled in the bottom of the tank or a foot valve with screen connected to the suction line of an above-grade suction lift pump
- pump control systems that may incorporate additional in-line automatic flush filters, sand separators and wye strainers
- filters and/or screens on automatic control valves and sprinkler heads

While these filtering mechanisms will remove enough solid type materials from entering and clogging the nozzles and orifices of the points of distribution whether they be drip emitters or sprinkler heads, these filters will do little to prevent chemicals that may have an adverse impact on plant growth and development.

New construction sites where redevelopment is replacing buildings that were built long before many building materials were considered hazardous to human health such as asbestos, lead based paints, zinc and mercury may still be present in soils and or surfaces that will be exposed to rain water prior to it reaching the catch basins. Not all these elements may prove detrimental to plant development but as shown in the example below, the results of water samples taken from a newly constructed memorial site in which storm water is being stored for both irrigation use and non-potable indoor use, elements such as alkaline, magnesium, potassium, chloride, bromide, nitrate, ammonia, sulfate and silica were present at levels that the Landscape Architect deemed unacceptable for use without treatment.

1	pH	6.8490	6.9580	7.0680	7.2700		
2	Conductivity (MMHS)	113.91	132.20	100.20	433.51		
3	Free Halogen (PPM)						
4	P-Alkalinity (PPM)						
5	M-Alkalinity (PPM)	15.600	16.000	15.200	21.600		
6	Calcium (PPM)	22.008	22.708	18.422	36.331		
7	Magnesium (PPM)	12.130	18.252	10.090	136.82		
8	Molybdenum (PPM)						
9	Zinc (PPM)	0.0250	0.0410	0.0140	0.0210		
10	Total Iron (PPM)	0.0850	0.1140	0.0490	0.1020		
11	Manganese (PPM)	0.0120	0.0130	0.0100	0.0180		
12	Copper (PPM)	0.0230	0.0260	0.0110	0.0160		
13	Aluminum (PPM)	0.0440	0.0520	0.0360	0.0560		
14	Silica (PPM)	3.8530	3.8780	3.6300	5.0190		
15	Nickel (PPM)	0.0000	0.0000	0.0000	0.0000		
16	Vanadium (PPM)	0.0060	0.0130	0.0060	0.0950		
17	Sodium (PPM)	8.3470	7.5420	6.5630	6.9720		
18	Potassium (PPM)	1.7220	1.6680	1.1950	2.8050		
19	Chloride (PPM)	14.704	18.420	12.838	106.82		
20	Bromide (PPM)	0.1570	0.2640	0.0000	2.1110		
21	Nitrite (PPM)						
22	Nitrate (PPM)	1.9630	2.0230	1.2120	2.1790		
23	Ammonia (PPM)	0.0841	0.0648	0.1510	0.7330		
24	Phosphonate (PPM)						
25	Ortho Phosphate (PPM)	1.8000	1.6800	1.7500	1.7100		
26	Total Phosphate (PPM)	2.0210	2.0380	1.9560	1.8090		
27	Sulfite (PPM)						
28	Sulfate (PPM)	6.5280	6.6120	6.7890	9.3010		
29	Total Azole (PPM)						
30	Glycol (PPM)						
31	Turbidity (NTU)	0.9800	1.5300	0.5900	2.2000		
32	Aerobic Bacteria (Cells/mL)	20	0	0	200		
33	Primary Organism	Pseudomonas Specie			Pseudomonas Specie		
34	Secondary Organism				Bacillus Specie		
35	DEAE (PPM)						
36	Morpholine (PPM)						
37	Cyclohexylamine (PPM)						

Stormwater collected for irrigation use was stored in a separate cistern from other non-potable water collection tanks and water sample testing results are shown in the far right data column. The conductivity (433.51 MMHS), magnesium (136.82 PPM), chloride (106.8 PPM), nitrate (2.179 PPM), sulfate (9.3010 PPM) and turbidity (2.200 NTU) were at levels higher than what were considered suitable for re-introducing back into the landscape environment through irrigation spray heads and drip tubing, especially in a public facility with high pedestrian volume. Little can be done to remediate water once it reaches the storage tank except diluting it with fresh water and in this particular example, it was an extremely large tank requiring a large amount of city water to flow into the tank.

The next example shows new data of samples taken 1 week later after water in the cistern was diluted by allowing city water to flow into the cistern and run-off channeled into the city sewer system.

1	pH	7.6150	7.7910	7.8080	7.3270		
2	Conductivity (MMHS)	80.400	423.18	436.05	92.400		
3	Free Halogen (PPM)		1.4400	1.7000	0.0300		
4	M-Alkalinity (PPM)	12.800	62.000	65.600	14.000		
5	Calcium (PPM)	13.585	27.624	27.532	15.847		
6	Magnesium (PPM)	5.1250	6.6440	6.5040	9.3950		
7	Molybdenum (PPM)						
8	Zinc (PPM)	0.0040	0.0990	0.0400	0.0110		
9	Total Iron (PPM)	0.0330	0.0300	0.0310	0.0720		
10	Manganese (PPM)	0.0080	0.0040	0.0040	0.0100		
11	Copper (PPM)	0.0160	0.0180	0.0150	0.0100		
12	Aluminum (PPM)	0.0350	0.0260	0.0280	0.0420		
13	Silica (PPM)	3.3510	6.1220	5.8530	3.1990		
14	Nickel (PPM)	0.0000	0.0000	0.0020	0.0000		
15	Vanadium (PPM)	0.0040	0.0050	0.0050	0.0060		
16	Sodium (PPM)	7.1020	68.605	72.369	6.7060		
17	Potassium (PPM)	0.6400	5.7120	6.6440	0.8280		
18	Chloride (PPM)	8.2130	28.656	29.199	11.038		
19	Bromide (PPM)	0.0000	37.217	38.349	0.1050		
20	Nitrite (PPM)						
21	Nitrate (PPM)	0.7330	2.3850	2.0890	0.3630		
22	Ammonia (PPM)						
23	Phosphonate (PPM)						
24	Ortho Phosphate (PPM)	1.9000	2.0900	1.9000	1.7400		
25	Total Phosphate (PPM)	2.0480	2.4030	2.3320	1.8940		
26	Sulfite (PPM)						
27	Sulfate (PPM)	5.3800	28.165	27.676	5.6820		
28	Total Azole (PPM)						
29	Glycol (PPM)						
30	Glycol E/P (%)						
31	Turbidity (NTU)	0.3500	0.0000	0.4200	0.9400		
32	Aerobic Bacteria (Cells/mL)		0	200	200		
33	Primary Organism			Pseudomonas Specie	Pseudomonas Specie		
34	Secondary Organism						
35	Coliform (Cells/mL)				0		
36	DEAE (PPM)						
37	Morpholine (PPM)						
38	Cyclohexylamine (PPM)						
39	Total Halogen (PPM)		>2.2	>2.2	—		

Levels of conductivity went from 433.51 MMHS to 92.4 MMHS, magnesium went from 136.62 PPM to 9.395 PPM, chloride 106.82 PPM to 11.038 PPM, nitrate 2.179 PPM to 0.363 PPM, sulfate 9.301 PPM to 5.68 PPM and turbidity went from 2.200 NTU to 0.94 NTU. Had water samples been tested prior to filling the tank, a considerable amount of city water could have been saved by allowing initial storm water to run off into the sewer system before being channeled into the cistern.

Once construction of site is complete and the landscape is established, collected rain-water quality can be impaired by the introduction of applied pesticides and herbicides to the landscape, hydro-carbons (Hydrogen-Carbon organic compound found naturally occurring in crude oil) or other petroleum based products spilled on parking lot surfaces as well as ice-melting compounds that are carried by run-off rainwater into the stormwater collection system. There are various methods of filtering and/or treating water with these impairments and will be reviewed in the following pages.

Salinity Management

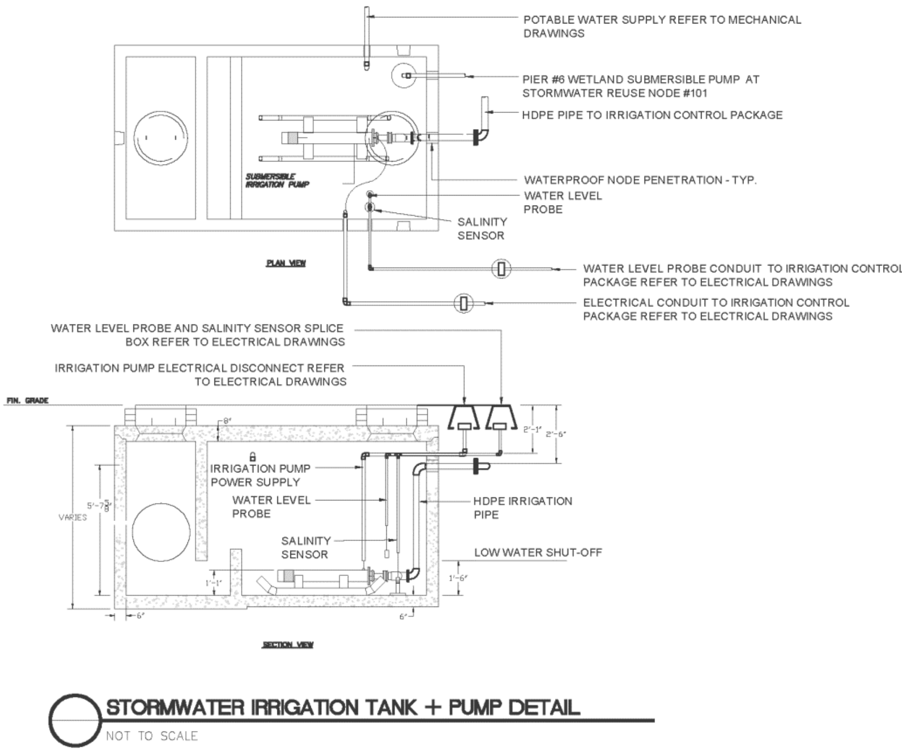
Nature can provide a challenge to irrigation water quality where landscapes such as parks and playing facilities that are on ocean waterfront property and are subject to high levels of salt after storm surges and high winds carry sea spray hundreds of feet in-shore. Salinity is a term used to describe a concentration of (ionic) salt species including calcium(Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), chloride (Ci^{+}), bicarbonate (HCO_3), carbonate (CO_3^{2}), sulfate (SO_4^{2}) and others. Salinity is expressed in terms of electrical conductivity (EC) and is measured in units of millimhos per centimeter, micromhos per centimeter or deciSiemens per meter. The EC of a water sample is proportional to the concentration of disolved ions in the water sample, hence the EC is a simple indicator of total salt concentration. High concentrations of salt in soils compete with plants for available water. Some salts have a toxic affect on plants and can burn roots and/or foliage. High concentrations of sodium in soils can lead to a high dispersion of soil aggregates, thereby damaging soil structure and interfering with soil permeability. (Institute, 2012).

Water and soil sample analysis is necessary to monitor which salt species are present and at what levels to determine the potential risk to plants, especially during irrigation season. Standard laboratory analysis will include total concentration of salinity expressed as EC or as Total Disolved Solids (TDS). Different plant species have different tolerances to salinity and the test results should be reviewed by a turf grass or plant science specialist.

Salinity levels may also increase due to stormwater run-off from parking lots, roads and sidewalks where de-icing treatments are applied periodically prior to and during winter storm events. Many de-icing treatments are derived from all natural agricultral products and renewable resources which pose little threat to landscape plants and grasses however salinity levels increase in storm water catchment systems due to the presence of sodium chloride (natural brine), magnesium chloride and potassium which depending on the solution are combined with the natural ingredients for effectiveness. Since these products are applied in winter, the harmful effects of these treatments is usually minimized by the diluting effect that spring rainfall events have in washing away these products before storm water is captured for irrigation use, however analysis of water samples taken prior to refilling cisterns or tanks may reveal the need to divert initial rainfall to a run-off site.

Mitigating salinity levels in captured storm water and minimizing any potential harmful effects to the landscape is achieved by implementing some common irrigation practices in product selection and the scheduling of irrigation cycles. Water applied either at surface or subsurface level to plants reduces the risk of foliage damage as well as most of the products that apply water in this fashion are also the more efficient method of irrigation. Better efficiency helps prevent over-watering thereby helping reduce levels of salts being applied to the landscape. Scheduling irrigation cycles with less frequency and longer runtimes promotes not only deep root growth but also may provide a leaching affect to salts already in the soil structure.

Monitoring salinity levels in water collected for irrigation use can be achieved by incorporating salinity sensors which are typically suspended in the cistern or holding tank by a pull rope similarly as the water level sensor is suspended. In-line sensors are also available for monitoring salinity prior to intake to the cistern. The salinity sensor monitors EC levels and communicates to the pump control center via hardwire cable. High-low salinity level parameters are pre-set in the control panel and will over-ride pump starts if levels exceed parameters. The following Stormwater Irrigation Tank and Pump Detail is of a stormwater catchment node installed at a municipal coastal waterfront park.



Typical Stormwater Irrigation Pump Detail Showing Salinity Sensor

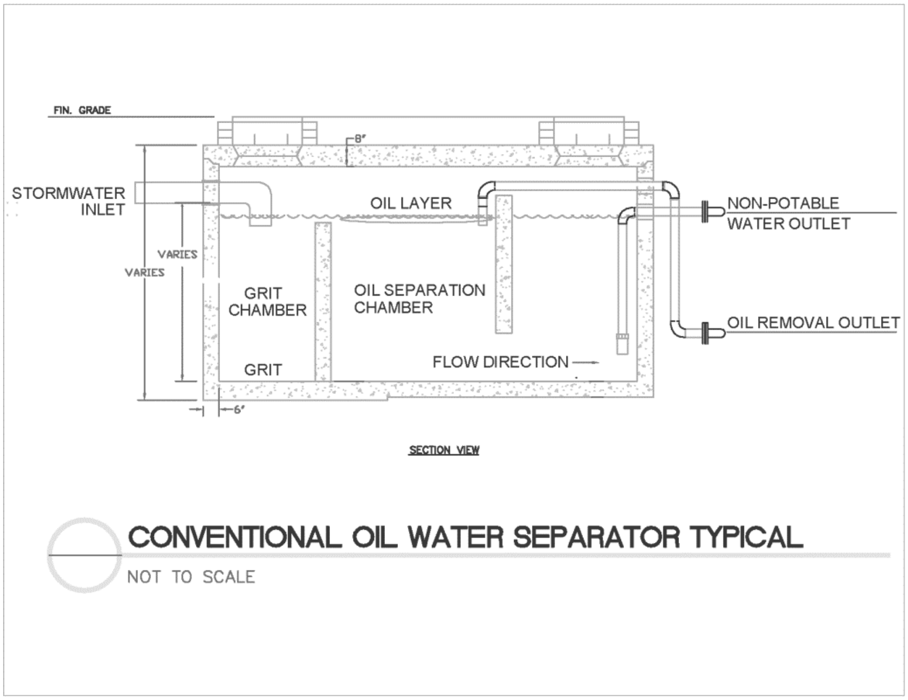
When salinity levels exceed that which are safe to apply to the landscape, a course of action to reduce salinity in the system will depend on what design elements were incorporated into the system to deal with salinity. Most cistern systems are designed with a connection to a potable water source to provide a back-up supplement to stormwater collection along with a discharge outlet to allow excess water to run-off into storm sewer systems, retention ponds or biofiltration areas. Allowing potable water to enter into the holding tank and releasing over-flow levels to run-off areas, salinity level will drop as stormwater is replaced by fresh water. If salinity levels are monitored regularly, potable water can be tapped for diluting purposes at a flow rate that may prevent the necessity of having the entire stormwater contained in a tank to be flushed out the run-off outlet.

Of the many EC sensors available on the market today, the pictured example is typical of a suspended type sensor which this particular unit also provides data on water temperature.

Hydro-Carbon Filtration and Treatment

Hydro-carbons are introduced into the stormwater collection system in a variety of ways from within the landscape. Oil or gas spills on parking lot surfaces, run-off from vehicle washing centers, contaminated soils on construction sites and leaking dumpsters.   In most cases, incidents of spills and leakage occur infrequently and require immediate remedial action in containing and removing the pollutants before they reach water sources however some facilities utilizing reclaimed water sources for non-potable use may require installation of an oil water separator to extract hydro-carbons from the run-off water.

Oil water separators are passive, physical separation systems designed for removal of oils, fuels, grease and hydraulic fluids from water. There are two types of water separators in use today. The oldest type is gravity or conventional separation, with simple separation via gravity (density differential between two immiscible liquids leading one of them to rise above the other). This system, when designed properly provides a certain tank length, width and depth that maintains a wide, quiet spot in the pipeline to give oils time to rise. This design, also known as an API (American Petroleum Institute) separator, generally provides a discharge of oil in the concentration of 100 parts per million based on a 150 micron droplet size. The API type design relies on a large water volume which in turn requires a large tank compared to the coalescing separator system.



The above diagram outlines the conventional or gravity type separator tank in which storm water enters the tank from the left and is allowed to flow slowly from the grit collection chamber to the oil separation chamber where oil droplets coalesce, float to the surface and are prevented from flowing beyond the barrier wall. The cleaner water flows under the barrier wall and is drawn out of the tank by a suction lift pump utilizing a suction line with foot valve. Oil contained in the oil separation chamber is siphoned off by a separate pump and directed to the waste oil containment tank.

The newer separator design or coalescing separator utilizes coalescing plate(s) available in a variety of designs but all having a relatively large enough surface area to collect oil particles as they pass by and allowing them to coalesce into larger droplets which then are able to float to the surface of the water level in the tank and be collected for removal from the system. (*www.oil-water-separator.net/separators-coalescing-theory.html*. (2004). Retrieved August 22, 2012, from www.oil-water-separator.net: http://www.oil-water-separator.net.)

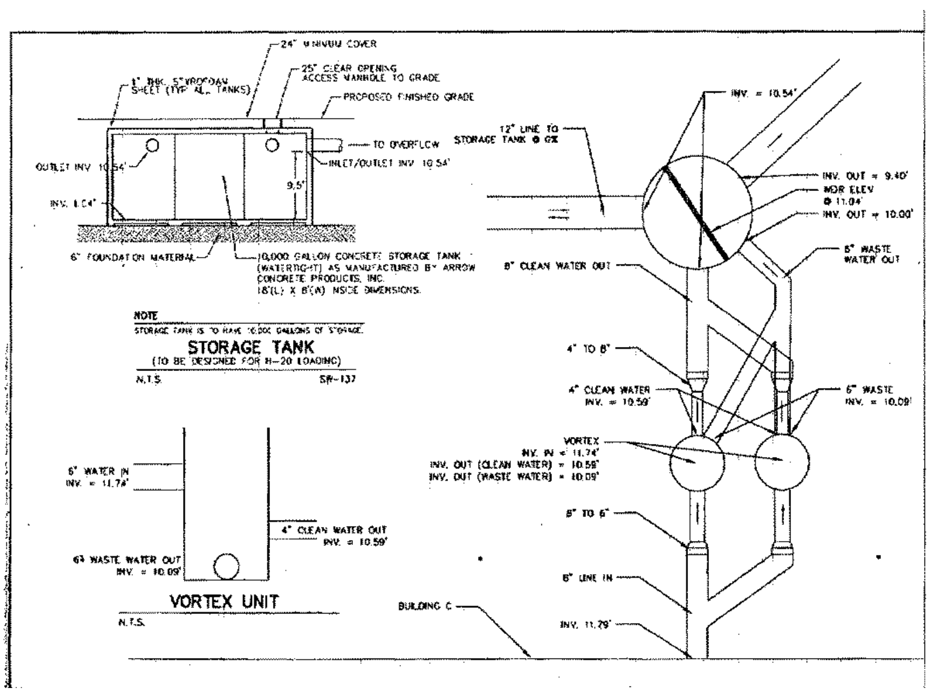
Sites utilizing stormwater collection systems should have water and/or soil samples analyzed prior to storing for re-release into the landscape to determine if the presence of hydro-carbons exist. Adding oil-water separators to stormwater collection systems will easily add tens of thousands of dollars in materials and installation costs to a project.

There are a multitude of oil water separating units, each designed for specific applications including treating industrial waste, run-off from vehicle washing facilities, drains from kitchen facilities and vehicle service stations.

Pre-Filtration Devices

Depending on which contaminates are present within a site, there are many products available to prevent contamination of irrigation water prior to entry into the storage and distribution system. Catch basins and piping systems that feed cisterns and/or retention ponds can begin the filtration process by incorporating initial or pre-filtration units that include vortex filters, gravity-type in-line rain water filters, first flush diverters and screens on pump suction lines.

The diagram below outlines the flow of storm water collected from an apartment building roof-top and parking lot with catch basins feeding an 8” drain pipe. The 8” drain pipe splits in two 6” pipes that each feed a separate vortex filter. Storm water is filtered and clean water is directed to a 4” outlet and waste water exits the vortex via a 6” drain pipe. The 2, 4” clean water pipes are sized up to 6” and are joined prior to entering a separation chamber. Waste water also is pipe to the separation chamber. Clean water at this point can either be allowed to flow to the storage tank for irrigation use or re-directed to the waste water out flow should the storage tank be full.



First flush filters or flush water diverters help maintain water quality prior to storing for landscape irrigation use by preventing the first flush of water to reach the tank and instead diverts it to a debris chamber. Diverters can be installed in downspouts, above ground on posts or wall-mounted, below grade as pictured above. This below-ground first flush diverter in which initial run-off from parking lot and/or roof tops is flushed of the bulkiest materials and clean water is directed to storage tank while debris that is trapped in the diverter chamber is gravity drawn to an outlet and sent to waste water area.

Conclusion

In many states, the regulatory and permitting process governing how stormwater run-off is to be controlled and how it can be used has been relegated to water purveyors who under the auspices of state and local governmental agencies, insure that water quantity and quality are protected for public access. Water purveyors as well as local, state and federal government agencies also have influence over how reclaimed water sources such as stormwater collection systems, whether it be roof top rainwater harvesting or sidewalk and parking lot drainage systems can be used as an irrigation supply for landscapes in both private and public facilities.

This paper provides only a very brief overview of some of the potential water quality issues that are present when utilizing stormwater for reuse. Products for every aspect of reclaimed water systems are available from manufacturers worldwide, with some specializing in only one particular component such as a sensor, a filter or a tank while some companies offer complete systems.

Design considerations should bear in mind the old adage “An ounce of prevention is worth a pound of cure” which is very appropriate when it comes to preventing stormwater contaminates form being reintroduced into the landscape. Recognizing what contaminates may already be present in at a particular construction site or what potential contaminates may be introduced into stormwater run-off as the landscape is maintained will help determine which products or what type of system will best serve to improve water quality. To properly design an irrigation system that incorporates stormwater as a supplemental or even primary water source requires a team effort that includes the input from the civil engineer to provide anticipated flow rates based on topography and area square footage, the landscape architect to provide plant tolerances to salinity and plant water requirements, lab testing facilities to provide soil and water analysis and the property management company as to how the system will be maintained and water quality monitored.

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Turfgrass ET from Small Weighing Lysimeters in Colorado: Two Season Results under Adequate Moisture Conditions

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Abstract. *The purpose of the study was to quantify evapotranspiration of several varieties of turfgrass, under adequate moisture conditions and with adequate fertility, for use with SMART irrigation controllers. Small weighing lysimeters were planted to 10 different turfgrass species or mixes in 2010, including 9 cool season grasses and 1 warm season mix, with four replicates of each turfgrass. Measured daily ET was compared to ETos calculated using data from an adjacent weather station and the standardized Penman-Monteith equation. The results from 2011 and 2012 are presented.*

Each lysimeter is centered in a 4-ft by 4-ft plot of the same grass variety. All grasses are mowed to the same height of 3 inches. The lysimeters each consist of a PVC shell containing a 12-inch diameter, free-draining sandy loam soil core having a 20-inch rooting depth. The lysimeters are continuously weighed in-place by electronic load platforms connected to a data logger. Irrigation is applied via high uniformity sprinklers and measured through a flow meter monitored by a data logger. All turfgrasses are irrigated on the same schedule and are managed to avoid soil moisture induced stress – all received the same base watering. As needed, supplemental hand watering of each individual lysimeter was accomplished to bring each back to field capacity following each irrigation event.

A table of the average ratio of measured turfgrass evapotranspiration to calculated ETos over the growing season is presented in the Summary.

Keywords. Turfgrass ET, weighing lysimeter, plant factor, crop factor, deficit irrigation.

Procedures

Background

The direct measurement of turfgrass ET using weighing lysimeters provides a defensible basis for quantifying and comparing actual water use to ETos from the standardized Penman-Monteith equation. This information will assist in the programming of weather-based SMART controllers. It can also be utilized by municipalities to develop landscape irrigation standards in support of efficient water use and conservation.

A previous paper by Crookston, et al. (2010) included an overview of several previous studies regarding turfgrass ET. A second paper by Crookston, et al. (2011) included preliminary results from the 2011 season.

Methods

In 2009, Northern Water commenced construction and installation of a 30-ft x 30-ft study plot for turfgrass lysimeters within its Conservation Gardens at its headquarters in Berthoud, Colorado. The turfgrasses were seeded starting May 28, 2010, and finishing June 2, 2010. However, frequent sprinkler irrigations for establishment of the turfgrasses continued through most of July 2010. The top rim of most lysimeters was still clearly visible and the effective diameter of the lysimeters did not fill the small gap surrounding all lysimeters until after that time. Consequently, the 2011 season was the first full season for evaluation of ET from established turfgrasses.

The lysimeter plot was divided into 4-ft x 4-ft sub-plots, separated by 1-inch x 6-inch PVC plastic composite decking/edging material. This edging clearly delineated the subplots and helped prevent the spread of one grass variety into another subplot. It also provided support for foot traffic by study technicians without damage to turf or compaction of the soil. Turfgrasses were planted into 44 of the 49 sub-plots. The four corners and center sub-plots were not included in the study, but were planted to a bluegrass blend to maintain fetch. The lysimeter plot was divided into four blocks, with each block containing 11 randomized sub-plots with lysimeters, one of each turfgrass variety initially included in the study. However the Ephraim crested wheatgrass did not thrive and by 2012 was significantly contaminated by adjacent grasses. It was subsequently dropped from consideration. Consequently, the study included four replicates of each of the following 10 turfgrasses:

Table 1. Turfgrasses (seed mix by weight)

Blue gramma – buffalograss mix	70% Blue Gramma & 30% Buffalograss
Drought hardy Kentucky bluegrass	33% Rugby, 33% America & 33% Moonlight
Fine fescue mix	25% Covar Sheep, 25% Intrigue Chewings, 25% Cindy Lou Creeping Red & 25% Eureka Hard
Kentucky bluegrass blend	50% Rampart, 25% Touchdown & 25% Orfeo
‘Low Grow’ mix	29% Creeping Red fescue, 27% Canada bluegrass, 24% Sheep fescue & 16% Sandburg bluegrass
‘Natures Choice’ mix (Arkansas Valley)	70% Ephraim Crested wheatgrass, 15% Hard fescue, 10% Perennial ryegrass, 5% Kentucky bluegrass
Perennial ryegrass	Playmate blend
Reubens Canada bluegrass	
Tall fescue	Major League blend
Texas hybrid bluegrass blend	50% Reveille & 50% SPF 30

Equipment

The weighing platform for each lysimeter includes a Revere PC6-100kg-C3 load cell transducer. Each load cell is connected to one of three AM 16/32 multiplexers, each connected to a Campbell Scientific CR10X data logger. Every three seconds a measurement is taken from each load cell. These measurements are averaged every 60 seconds. This 1-minute average is time-stamped and stored in the data logger at the end of each 15-minute period. Stored data is automatically downloaded every 15 minutes to a desktop PC via an RF401 spread-spectrum radio. Differences in lysimeter weight are calculated as the difference in the measurement at the end of each hour. These hourly values are compared to calculated ETos obtained from the REF-ET software v.3.1.08 (http://www.kimberly.uidaho.edu/ref-et/) utilizing data from the adjacent Campbell Scientific ET-106 weather station. The weather instruments are each calibrated annually.

The weighing platforms for each lysimeter were calibrated in-place (without the lysimeters) in September 2009 over their full load range using steel weights. The platforms were again re-calibrated in-place during 2010, but only over their operational range (from dry soil to wet soil). In-place re-calibration was again performed in early March 2011. No problems were identified during the re-calibrations, and all weighing platforms were measuring lysimeter weights properly.

The entire lysimeter plot is on a single irrigation zone using MP Rotator 2000 sprinklers on 15-ft spacing. A DLJ ¾-inch x ¾-inch brass flow meter with pulse output is connected to a Campbell Scientific data logger which measures all irrigation applications to the lysimeter plot. In addition, 15 Texas Electronics tipping bucket rain gauges are installed flush with the turf height throughout the lysimeter plot to measure net irrigation application as well as rainfall.

Deep Percolation Effects Excluded

Deep percolation down through the lysimeters was not directly measured. Beginning in late July 2010, all sprinkler irrigations were scheduled for after sundown and before midnight. Because the lysimeters are free-draining with sandy loam soil only 20-inches deep, any deep percolation from irrigation was generally assumed to be completed within 24 hours. Hand watering to bring each individual lysimeter subplot up to field capacity almost always occurred the same day as the sprinkler irrigation, or the following day. The data following an irrigation event or significant rainfall was discarded from the analysis. Minor rainfall events were included, but with the calculated daily ET increased by the amount of rainfall. Any excessive percolate that ponded below a lysimeter was removed through a manually-controlled vacuum extraction system as needed.

Results and Discussion

Table 2 provides the average ratio of measured turfgrass evapotranspiration to calculated ETos during the 2011 and 2012 seasons for each of the 10 selected turfgrasses. Figure 1 presents the same data graphically, but on a time scale of cumulative growing degree days from greenup as a percentage of the cumulative growing degree days from greenup to effective full cover (beginning of peak use period). As expected, these data clearly indicate reduced water use in the Spring season with peak water use occurring during mid-Summer. Although some differences between different turfgrasses are evident, these data are preliminary and should not be relied upon until further more in-depth analysis and additional seasons of data are included for evaluation.

Table 2. Cool Season Turfgrass Kc_{os}, preliminary data.

Calendar month	Blue gramma – buffalograss mix	Drought hardy Kentucky bluegrass	Fine fescue mix	Kentucky bluegrass blend	‘Low Grow’ mix	‘Natures Choice’ mix	Perennial ryegrass	Reubens Canada bluegrass	Tall fescue	Texas hybrid bluegrass blend
Mar	-	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.08	0.07
Apr	0.16	0.41	0.44	0.41	0.42	0.43	0.39	0.37	0.44	0.40
May	0.35	0.68	0.73	0.69	0.70	0.72	0.66	0.64	0.72	0.67
Jun	0.70	0.85	0.87	0.85	0.86	0.89	0.86	0.82	0.85	0.83
Jul	0.88	0.92	0.89	0.90	0.90	0.94	0.92	0.90	0.87	0.87
Aug	0.88	0.94	0.90	0.91	0.90	0.95	0.93	0.91	0.87	0.88
Sep	0.85	0.93	0.91	0.90	0.89	0.95	0.92	0.91	0.88	0.87
Oct	0.81	0.90	0.91	0.88	0.87	0.94	0.90	0.91	0.87	0.85
Apr-Oct	**0.66**	**0.80**	**0.81**	**0.79**	**0.79**	**0.83**	**0.80**	**0.78**	**0.79**	**0.77**

For use with ETos for established turfgrass stands, well-watered, and experiencing seasonal (winter) dormancy periods. Turfgrass Kc = Measured Turfgrass ET / ETos adjusted for Ks (soil moisture stress).

Figure 1 illustrates the procedures for normalizing Kc curves based on growing degree days. Under this timeline, the similarity of the Kc curves is striking. It provides more accurate application of Kc curves during different growing season, whether hotter and longer, or shorter and cooler than average. The 2012 season was significantly warmer and longer than cooler 2011 season, however the Kc data from both season compared closely to one another. Further detail is available from Allen 2007.

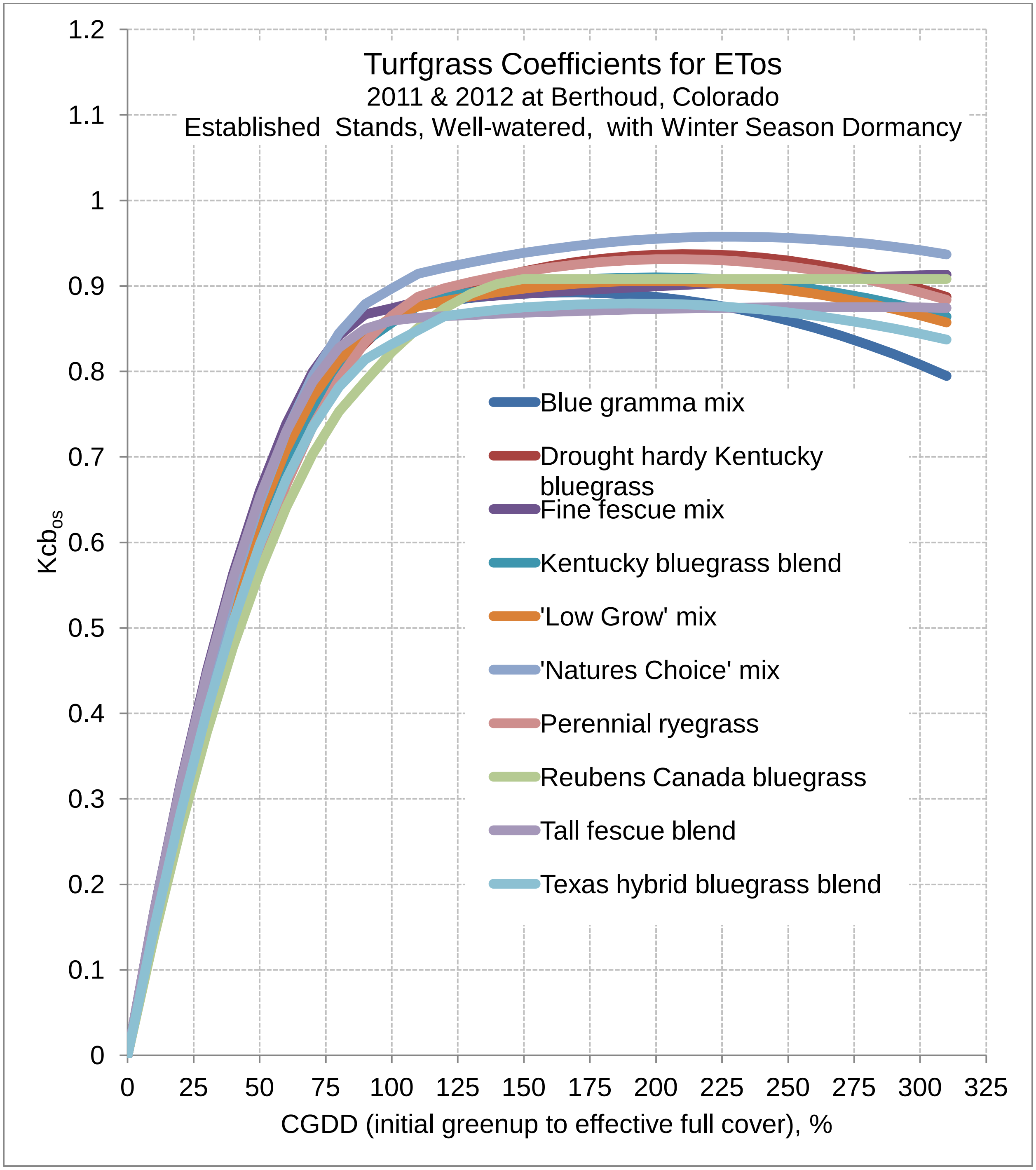

Figure 1. Small Turfgrass Lysimeters, 2011-2012, preliminary data. Average ratios of measured turfgrass ET to ETos for 10 turfgrasses in Northeastern Colorado. Turfgrass Kcb = Measured Turfgrass ET / ETos adjusted for Ks (soil moisture stress).
GDD = max((Tmax+Tmin)/2-Tbase,0) with Tmax, Tmin and Tbase in Deg C. Tbase = 0 and 10 for cool season and warm season turfgrasses respectively. CGDD (cumulative growing degree days) Greenup to Effective Full Cover = 1300 and 550 for cool season and warm season turfgrasses respectively.

Conclusions

Additional seasons of data collection are necessary to fully establish the plant water use coefficients for the various turfgrasses. Future plans include study of turf water use under deficit or significantly reduced irrigation management. It is anticipated this information will be of particular value in programming and adjusting irrigation controllers to adjust for the reduced water use of turfgrasses during the Spring season and to better maintain turfgrass vigor and health during the mid-summer period of greatest water need. Previous approaches utilizing a constant turfgrass coefficient all season can be readily improved, resulting in potential for increased water conservation and improved landscape appearance.

Acknowledgements

The high quality of the collected data for this study was directly attributable to the professionalism and work ethic of Ron Boyd and Chad Kuhnel. Both are employees of Northern Water, working in the Conservation Gardens and accomplished the majority of the work to construct, install and establish the lysimeter study plot.

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Landscape Coefficients Derived by Soil Water Balance in Xeriscape Plantings

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Abstract. Four foot deep profile soil moisture sensors (each with 5 measurement segments) were installed in 8 unique drip-irrigated Xeriscape Gardens at Northern Water in August 2011. Plant groupings (no turf) represented a spectrum of plant sizes and types in the Xeriscape Gardens. Soil moisture was monitored weekly until November 2011, when monitoring intervals were lengthened to 2-3 weeks through the winter. Plant condition was routinely observed during the growing season. Bi-weekly readings were resumed at the beginning of April 2012 and weekly readings resumed in May 2012. A soil water balance was calculated for irrigation and precipitation-free time periods and compared to ETrs and ETos reference evapotranspiration calculated from an adjacent weather station to derive landscape coefficients. Soil moisture drawdown at each of the 5 soil depth intervals was observed for each plant grouping, with inference for rooting depths and soil water extraction zones.

Keywords. Landscape ET, landscape coefficient, landscape irrigation, landscape water use.

Introduction

Xeriscaping is promoted as a set of landscape water conservation principles. Efficient irrigation systems, non-turf irrigation zones separate from turf zones, and plant selection are some of the principles of water-efficient landscaping. However, plant selection is often heavily emphasized, while irrigation needs are mostly not quantified. Urban residential landscapes are each unique, with varying microclimates, exposures, and plant selections. Therefore, it is difficult to quantify irrigation needs in ways that are easy to understand and implement. Frequently, plants are categorized as having very low, low, medium, or high water requirements. The categories typically refer to percentage of reference evapotranspiration (ET) (0-25%, 25-50%, 50-75%, 75-100%).

Other complexities in developing irrigation guidelines for landscapes include the fact that many landscapes contain mixed plant types (trees, shrubs, perennial plants). Xeriscape irrigation recommendations usually stress that plants of different water needs be in separate hydrozones.

One method of estimating landscape water needs was presented by University of California Cooperative Extension California Department of Water Resources (2000). This document presents the Landscape Coefficient method of estimating irrigation needs and WUCOLS III, the acronym for Water Use Classifications of Landscape Species. The landscape coefficient method borrows extensively from the agriculture crop coefficient methodology, with the limitation that landscapes are usually not monocultures as are agriculture fields. While the crop coefficient methods work well for turf, mixed species and non-uniform landscapes are not well-suited for this approach. Other techniques for quantification of mixed-species landscape water are being developed and tested.

In Texas, Pannkuk et al (2010) found that mixed-species urban landscapes on non-sodic sites ranged from 0.5 to 0.7 K_L (based on ETo) under well-watered conditions, stating that landscape irrigation based on reference evapotranspiration can achieve significant water savings.

Sun et al (2012) found that under well-watered conditions, plant water requirement categories were not the controlling factor in determining landscape water use. Instead, plant canopy cover determined water use for woody species and perennials. It was suggested that adjusting planting density could achieve water savings in the well-watered urban landscape. Drought-adapted plant selection was acknowledged to likely play a bigger role in maintaining an attractive landscape with reduced irrigation and water-deficit conditions. Plant factors (K_P) in the well-watered, replicated landscapes ranged from 0.3 to 0.9 (woody plants) and 0.2 to 0.5 for perennials. After adjustment for canopy cover, well-watered landscape factors ($K_{L,}$ based on ETo) ranged from 0.6 to 0.8.

Recently, efforts to quantify xeric landscape irrigation needs in northwestern New Mexico were presented by Smeal et al (2010), who recommended an average landscape coefficient (K_L) of 0.3 ETrs (tall canopy reference evapotranspiration , ASCE-EWRI, 2005). Visual quality was the key factor in determining the appropriate irrigation level. Many of the plants grown in Smeal et al (2010) are available and viable in Northern Colorado; therefore the K_L selected in that study was considered an appropriate starting point for xeric landscape irrigation in Colorado.

As in Smeal et al (1010), however, our study is also not a replicated study. It is, instead, an investigation of eight xeric landscape responses in northern Colorado to irrigations at approximately 0.3*ETrs. The objectives of the project were to: to evaluate plant complex water use via soil water balance, to infer active rooting depths from soil moisture changes at different depths in the soil profile, and to evaluate the irrigation practices in the landscapes with regard to maintaining landscapes for low water use or demand, as well as appearance.

Methods

Eight mini-landscapes were built from 2004-2005 at Northern Water's headquarters in Berthoud, CO. Each landscape was designed with a 'shrub' zone and a turf zone, each with different themes, plant mixtures, and irrigation zones. ('Shrub' zones included small trees, shrubs, and perennial plants.) All plants included were 'Colorado-friendly', meaning that plants could survive in Colorado's semi-arid climate with considerably less irrigation than cool-season turf. Each 'shrub' irrigation zone contains mixed small trees or large shrubs, ornamental grasses of varying heights, or other small xeric plants.

The native soil is a Nunn Clay Loam (Fine, smectitic, mesic Aridic Argiustolls), which was amended with high quality organic matter. All turf zones were irrigated separately from the plant/shrub zones. Seven of eight non-turf zones are irrigated with some form of drip irrigation and scheduled separately from turf.

In 2011, 24 four-foot long MoisturePoint (E.S.I. Environmental Sensors, Inc., Sydney, BC, Canada) soil moisture sensors were installed in the eight landscapes. Three probes were installed in 6 landscapes; 4 in a seventh zone, and 2 in an eighth zone. Each sensor had 5 measurement zones, beginning with two six inch zones for the top foot, while each zone below was 12" in length. Soil moisture data were collected weekly with the MP-917 data-viewing instrument, starting on 9 August, 2011 through October, 2011, and continuing throughout the fall and winter with less frequency. In Spring, 2012, data collection intervals were more frequent and based more on bracketing irrigation events and rainfall events, when feasible.

A simple soil water balance was calculated for all measurement intervals, resulting in an ET estimate for the time interval. Intervals selected for analysis had very little (< 0.25 inches) precipitation or irrigation. Calculation depths were limited to those depths with both end point soil moisture values less than field capacity (0.35 in/in), when drainage was considered to be zero. Estimated ET was then compared to ETrs at selected times throughout 2012. This paper primarily references ETrs for consistency with the methods of Smeal et al (2010), though K_L values were also calculated for ETos.

Two landscapes were chosen for analysis for this paper: B, a landscape that contains plants and turf native to the Intermountain West, and C, a landscape that contains native trees and shrubs as well as numerous yucca species. Within each landscape, one of the three MoisturePoint sensors was chosen for analysis. The plant complex at sensor B1 was: Pawnee Buttes Sandcherry (*Prunus besseyi 'Pawnee Buttes')*, Dakota Sunspot Potentilla (*Potentilla fruiticosa 'Fargo')*, and Prairie Sky Switchgrass (*Panicum virgatum 'Prairie Sky'),* Figure 1. At sensor C1, the plant complex consisted of New Mexico Privet (*Forestiera neomexicana)* Figure 2.

Figure 1. Location of B1 MoisturePoint sensor. The plant complex consists of Pawnee Buttes Sandcherry (*Prunus besseyi 'Pawnee Buttes')* in the foreground, Dakota Sunspot Potentilla (*Potentilla fruiticosa 'Fargo'),* just above the Sand Cherry in the photo, and Prairie Sky Switchgrass (*Panicum virgatum 'Prairie Sky',* just behind the white sensor cap.

Figure 2. Location of C1 MoisturePoint sensor. The plant complex consists of New Mexico Privet (*Forestiera neomexicana).* Note the white sensor cap in the lower left third of the photo.

Results

Soil Moisture Trends

A check of soil moisture patterns from installation through September, 2012, suggests that both plant complexes were dormant for most of the winter and into spring (Figures 3 and 4). New Mexico Privet soil moisture (Figure 4) showed no decline from early January 2012 through early May, 2012 at depths to 3 feet.

Soil moisture increased in mid to late spring at the 4 foot depth. Soil moisture was at field capacity at the 2 and 3 foot depths; soil moisture was less than field capacity for most of the winter and early spring, suggesting that drainage was not usually occurring through the top two feet.

Soil moisture at times declined below field capacity in the 0-36” depths in B1 and C1; however soil moisture was slow to decline to less than saturated conditions in the 4 foot depth. This is in part due to installation technique; the MoisturePoint probe is driven into a pilot hole, but in the heavy clay loam soils, water had to be added to lubricate the hole. While the 0-36” depths seemed to equilibrate in several weeks, the 4 foot depth has been very slow to drain and equilibrate. The data also indicate that at times soil moisture exceeds field capacity; therefore drainage from one depth to the next may be occurring.

Soil moisture at the 4 foot depth in B1 and C1 decreased throughout the summer of 2012. Provided that large precipitation events do not drain through the soil profile, that depth may become a working depth for plant soil water balance accounting in future years.

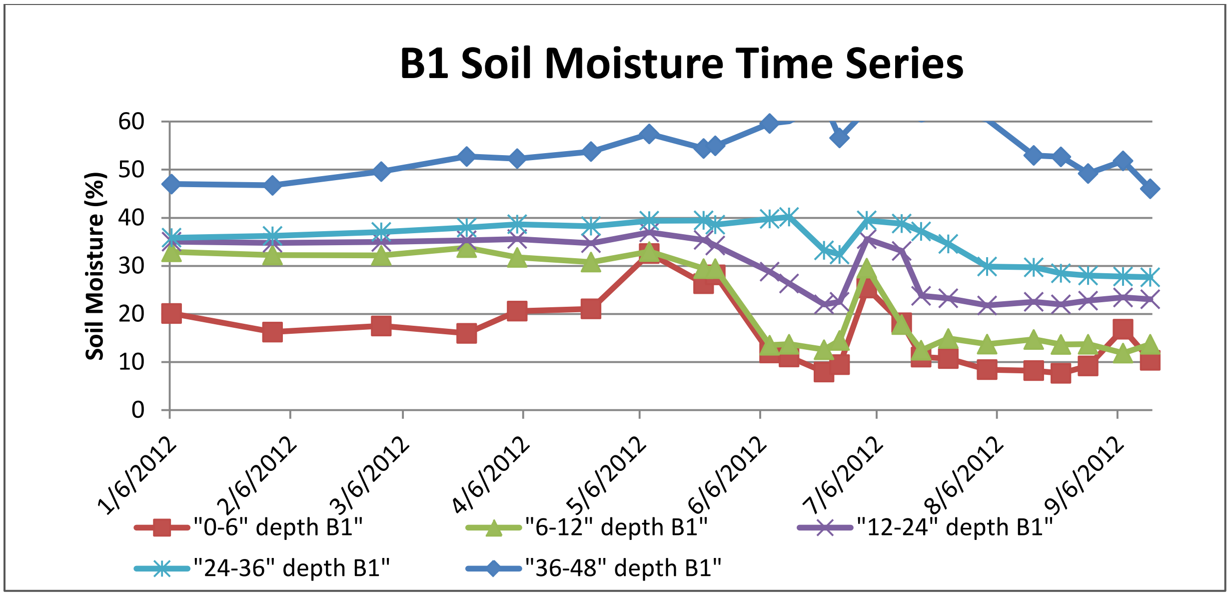

Figure 3. Soil moisture time series at each depth interval in the Pawnee Buttes Sand Cherry plant complex.

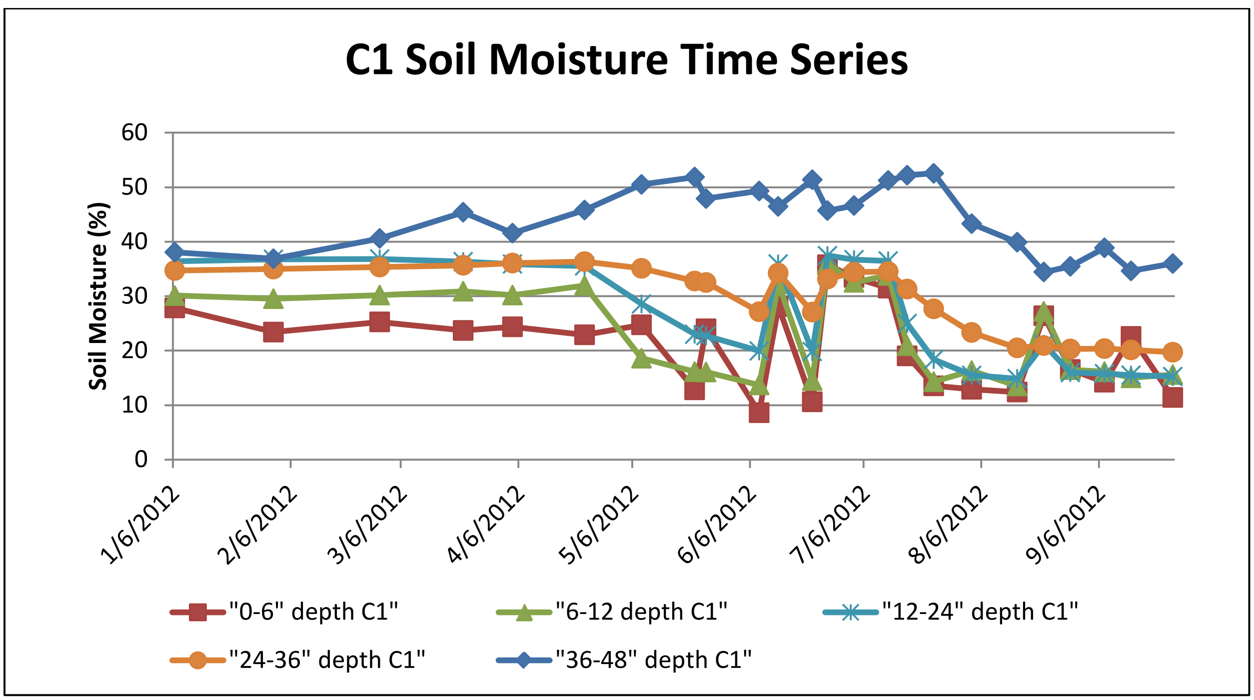

Figure 4. Soil moisture time series at each depth interval in the New Mexico Privet plant complex.

Soil Water Balance

A simple soil water balance was calculated for selected intervals during 2012. Intervals had very little or no precipitation or irrigation and soil depths included in each interval had soil moisture values less than field capacity. Filtered thus, drainage was assumed to be zero in the depths analyzed. The minimal precipitation and irrigation were accounted for in the soil water balance. Table 1 shows calculated ET from the soil water balance and ratio to ETrs for New Mexico Privet (C1).

Table 1. Estimated ET from soil water balance for the C1 (New Mexico Privet) landscape. Values in bold are the soil moisture depth increments used in the water balance in each date interval. The maximum and mean soil moisture values in each interval are shown.

Date Interval	Depth (in)	ET from SWB (in)	K_L (ETrs)	ETrs (in)	K_L (ETos)	ETos (in)	SM 0-6” (Max*/ Mean) *in interval	SM 6-12” (Max*/ Mean)	SM 12-24” (Max*/ Mean)	SM 24-36” (Max*/ Mean)
9/7-9/13/2011	36	0.74	0.63	1.18	0.76	0.97	**10.5/9.03**	**15.2/14.1**	**19.5/18.3**	**24.9/24.3**
2/29-3/22/2012	12	0.03	0.008	3.96	0.01	2.99	**25.3/24.5**	**30.9/30.6**	36.8/36.6	35.6/35.5
5/8/-5/22/2012	24	1.33	0.41	3.26	0.50	2.59	**24.7/18.8**	**18.6/17.4**	**28.6/25.8**	35.1/33.9
5/25-6/8/2012	24	1.33	0.45	2.96	0.58	2.29	**24.0/16.3**	**16.1/14.9**	**22.7/21.3**	32.5/29.8
6/13-6/22/2012	12	2.13	0.69	3.07	0.89	2.40	**28.1/19.4**	**28.1/23.4**	35.9/27.9	34.2/30.7
7/12-7/17/2012	12	1.38	0.91	1.51	1.15	1.20	**31.5/25.3**	**33.8/27.4**	36.5/30.7	34.5/32.9
7/17-7/24/2012	36	1.75	0.75	2.33	0.94	1.87	**19.0/16.3**	**20.9/17.6**	**25.0/21.7**	**31.3/29.5**
8/3-8/15/2012	24	0.23	0.07	3.24	0.09	2.56	**12.9/12.7**	**16.3/14.9**	**15.5/15.2**	23.3/21.9
8/22-8/29/2012	36	1.71	0.93	1.83	1.17	1.46	**26.4/21.5**	**27.2/21.9**	**21.2/18.6**	**20.9/20.6**

The ET values show water used in the interval at the particular drainage-free soil depth. The K_L value puts the ET in perspective and indicates that when soil water is available, New Mexico Privet can use as much water as turf (K_L of 0.91 from 7/12-7/17/2012). Yet, when soil water becomes more limiting, as between 8/3 and 8/15/2012, ET is very low at 9% of ETrs. The highest K_L values occurred in periods after an irrigation or rainfall, when soil moisture was high. Maximum and mean soil moisture values in each depth interval help illustrate this point.
The B1 plant complex, of much smaller statures than New Mexico Privet, used water at lower rates than New Mexico Privet (Table 2). Highest K_L values occurred in the interval after heavy precipitation or irrigation (7/12-7/17/2012).

It is apparent that K_L varies from interval to interval depending primarily on the availability of soil moisture. Lowest soil moistures tend to limit water use; this is expected from a native plant in the Intermountain West. An opportunistic water use pattern is also observed among many native plants in this region.

From 5/8-5/22, however, soil moisture was relatively high, but water use was low. This suggests that the B1 plant complex had not yet broken dormancy and begun using soil moisture. Photo documentary from 4 May, 2011 showed Pawnee Butte Sand Cherry blooming but nearly leafless, so it is plausible that the 5/8-5/22 2012 interval reflects a near-zero transpiration rate.

Table 2. Estimated ET from soil water balance for the B1 (Pawnee Butte Sand Cherry complex) landscape. Values in bold are the soil moisture depth increments used in the water balance in each date interval. The maximum and mean soil moisture values in each interval are shown.

Date Interval	To depth (in)	ET from SWB (in)	K_L (ETrs)	ETrs (in)	K_L (ETos)	ETos (in)	SM 0-6" (Max*/ Mean) *in interval	SM 6-12" (Max/ Mean)	SM 12-24" (Max/ Mean)	SM 24-36" (Max/ Mean)
9/7-9/13/2011	24	0.02	0.017	1.18	0.02	0.97	**6.6/6.2**	**15.2/14.8**	**24.3/24.0**	34.7/32.3
5/8/-5/22/2012	12	0.12	0.04	3.26	0.05	2.59	**32.6/29.4**	**33.8/31.2**	37.0/36.2	39.5/39.4
5/25-6/8/2012	12	1.56	0.53	2.96	0.68	2.29	**28.1/20.0**	**29.4/21.5**	34.2/31.5	39.8/39.1
6/13-6/26/2012	24	0.71	0.15	4.6	0.20	3.59	**11.1/9.5**	**13.7/13.1**	**26.3/24.2**	40.2/36.7
7/12-7/17/2012	12	0.93	0.62	1.51	0.78	1.20	**25.4/21.8**	**29.5/23.7**	35.6/34.3	39.4/39.1
7/17-7/24/2012	24	1.07	0.46	2.33	0.57	1.87	**18.2/14.6**	**17.8/15.1**	**33.1/28.4**	38.8/37.0
8/3-8/15/2012	24	0.10	0.03	3.24	0.04	2.56	**10.7/9.5**	**14.9/14.3**	**23.3/22.5**	34.6/32.2
8/22-8/29/2012	36	0.13	0.07	1.83	0.09	1.46	**8.2/8.0**	**14.7/14.2**	**22.5/22.3**	**29.7/29.1**

Not accounting for possible periodic drainage from 5/8/2012 to 9/25/2012, seasonal water use from the top 2 feet in the B landscape was 14.7 inches. ETrs for the period was 38.14 inches; therefore the seasonal K_L from the soil water balance was 0.385. The C landscape seasonal ET from the soil water balance was 12.9 inches; K_L was 0.34.

The ratio of applied irrigation plus precipitation to ETrs from May through September (K_L) was 0.37 for the B landscape and 0.35 for the C landscape.

Proportional soil water extraction by 12 inch increments in B1 and C1 for the 7/12-7/24 period is shown in Table 3. Potential drainage was neglected in the calculations, but would likely have been minimal for both locations. The third foot in the soil profile was more subject to potential drainage, but the data infer that far less soil water was extracted from this layer by the plant complex. Any soil water change in the 36-48 inch soil profile was considered to be drainage, as soil moistures were above field capacity on these dates. Soil moisture on 7/12/2012 was fairly high, but had decreased considerably in the 0-12 inch soil layer by 7/17/2012. Performing the same analysis for the 7/17-9/25/2012 interval showed a different distribution of soil water extraction (Table 3). As soil moisture decreased closer to the soil surface, soil water extraction tended to be greater from lower soil depths. A similar, but not as strong trend, was apparent for C1.

Table 3. Proportional soil water extraction by each 12 inch layer in the soil profile.

B1	0-12”	12-24”	24-36”
7/12-7/17/2012	75 %	19.7%	5.3%
7/17-7/24/2012	38.2%	52.8%	9.0%
C1			
7/12-7/17/2012	46.2%	42.2%	11.6%
7/17-7/24/2012	36.5%	41.1%	22.4%

Conclusions

Two plant complexes native to the Intermountain West were chosen to 1) to evaluate plant complex water use via soil water balance; 2) to infer active rooting depths from soil moisture changes at different depths in the soil profile and 3) to evaluate the irrigation practices in the landscapes with regard to maintaining landscapes for low water use or demand. .

While plant complexes were not quantitatively rated for appearance, occasional visual monitoring affirmed that the mini-landscapes remained in acceptable condition. Previous irrigation practices had generally followed the 25-50% of reference ET plant water need category, so this irrigation regime was not dissimilar to past years.

The ratio of applied irrigation plus precipitation to ETrs for the Pawnee Butte Sand Cherry complex in the B landscape was 0.37. The ratio of applied irrigation plus precipitation to ETrs for the New Mexico Privet complex in the C landscape was 0.35.

Soil water extraction was greatest in the top 12 inches when soil moisture was higher; as soil moisture decreased in the upper 12 inches, soil water extraction by plants increased at deeper depths. Understanding soil water extraction patterns will help irrigation scheduling and soil moisture sensor placement in landscapes with soil-moisture based controllers.

Seasonal water use for the B1 plant complex was 14.7 inches; the seasonal water use for the C1 plant complex was 12.9 inches. The K_Ls developed from a simple seasonal water balance, neglecting drainage, were 0.385 for the B1 plant complex and 0.34 for the C1 plant complex, very similar to the ratios of applied irrigation plus precipitation to ETrs. The estimated ET and K_L values in each time interval indicated that plants used water when available, but readily adapted to low soil moisture by reducing ET. The similarity of applied irrigation plus precipitation : ETrs ratios to the K_L values developed from the soil water balance implies that water applied will be water used, if drainage or runoff are not large factors.

It was apparent from the soil water extraction patterns that the plant complexes in this analysis were able to acquire moisture from soil depths of at least 24-36 inches. Also, weekly soil water measurement intervals revealed that the plant complexes used soil water heavily from the top 12 inches of the soil profile the first week after irrigation or precipitation events. Soil moisture was then extracted from the 12-24 inch soil depth in the second week.

Irrigation scheduling refinements may include extending the interval between irrigations. This analysis has not yet been extended to the smaller, shallower rooted plants. It is possible that plants with shallower root systems than shrubs, small trees, or tall grasses may not maintain appearance in an extended irrigation interval. Extension of the irrigation interval for the shrub, small tree, or large grasses will mean reduced ET over a longer period as the plants go into a soil-water-deficit induced dormancy state.

Further refinements to this project include modeling the drainage component to more thoroughly quantify the seasonal and interval soil water balances, and extending the analysis to every sensor in the eight mini-landscapes. Accounting for drainage will likely reduce the soil-water balance based K_L values. The results of the refinements will be used to modify irrigation and water conservation practices and recommendations. Reduction of total applied irrigation is also a goal, based on the current analysis.

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Municipal use of central control systems for the purpose of conserving water and reducing operating costs

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Abstract

Many municipal regions are experiencing a reduction in natural precipitation. Irrigation is becoming increasingly more necessary for providing the soil moisture required by the plants. At the same time the availability of water from our rivers, reservoirs, aquifers, etc is being strained. The public and competing user groups are applying pressure to restrict the use of irrigation and landscaping. There is a way to retain landscapes and continue using irrigation systems through the application of advanced water management control systems.

The City of Calgary operates the largest system of this type in the world conserving 10's of millions of gallons of water per year and millions of dollars in labor costs every year.

This paper explains the control systems, processes, staff training and hiring practices necessary for an organization to meet the challenges of operating parks and landscapes in the realities of a 21st century climate.

Introduction

The City of Calgary is located on the eastern slopes of the Rocky Mountains. It is a semi-arid area subject to low overall precipitation, drying winds, intense thunder storms, relatively hot summers (low 30's Celsius, high 80's to low 90's Fahrenheit), cold winters (-30 to -40 C, -22 to -40 F) and Chinook winds. Its domestic water supply comes from the snow and glacier melt in two Rockies watersheds dammed within the city limits.

Calgary is a single municipality of 1.2 million people covering 848 square kilometres (327.4 square miles). It is the capital of Canada's energy industry, and has been for close to 50 years. The city is home to many of Canada's oil and gas producers, and is the decision-making hub and head office location of every energy company doing business in the country. Other industries comprising Calgary's business sector include financial services, transportation and logistics, film and creative industries, niche information and communications technologies, manufacturing, agri-business, health and wellness, and tourism.

The City of Calgary Parks department maintains over 5,300 sites covering over 7,800 hectares (19,274 acres).

The City of Calgary Parks Water Management unit operates, maintains and manages over 2,300 irrigated sites covering more than 2,500 hectares (6,177 acres). With less than 60 people this is a monumental task.

In 1994 Parks began implementing an irrigation central control system in order to manage the application of water and to conserve the resource. The program started with 12 parks and has grown to approximately 1,200 in 2012. Calgary's system is the largest automated landscape irrigation control system in the world.

There have been many challenges related to the development and expansion of Calgary's central control system however without it The City would not be able to effectively and efficiently provide water to the plants that make up its world class parks.

Water Management Challenges

Technology

For a municipality or another large institutional landscape water manager, to be successful in their implementation of a central control system they must be aware of the challenges around its procurement and implementation. They must also be knowledgeable in other technologies.

To truly be successful in implementing a Central Control System the buyer/operator must realize that *a central control system is not merely an irrigation system that communicates but rather it is a communication system that irrigates*. Why this distinction? Because communication technology is far more complex and difficult to implement successfully than irrigation control. Adding a radio to an irrigation controller does not provide the end user with an effective central control system.

We will demonstrate the concept using an example from a different field. NASA's Apollo program was full of great engineering, design and construction not unlike what we see in many of the brands of irrigation controllers on the market today. However, no mater how good the engineering of those rockets, and how powerful the engines were, there was one enormous problem. The Apollo spacecraft was incapable of carrying the required computing power to control the space crafts, both command module and lunar module, to the moon and back. Therefore somehow the commands from the computers on the ground and the information from the sensors on the spacecraft had to be exchanged and that required a sophisticated and robust/reliable communication system or nobody was going to be going anywhere. So now imagine the advantages of having a central control system manufactured by a communications company.

Research into communication technologies will expose the individual to terms and acronyms such as RS232, RS485, MODBUS, MDLC, 7 layer OSI network Reference Model, TCP/IP, CDMA, GPRS, analogue, digital, etc. These are all terms, concepts and technologies that must be understood if a water manager is going to realize the benefits of central control system and have a successful system. As the end user starts to recognise the differences between one system's communication technologies and the other, the potential advantages and disadvantages will focus the search and narrow the field of choices. If a water manager finds themselves outside of their realm of expertise they should hire a consultant who is an expert in this field.

The next challenge is the power source. Is AC power available? Can the system work from battery (DC) power? How long can the system run on a certain size battery? Can it be powered by solar panels? Is this a third party modification or part of the standard offering?

Next are questions about sensors/inputs. Do you need digital (i.e. on-off pulses) or analogue (such as pressure sensors use or TDR soil moisture sensors use)? Is the system required to monitor revolutions per minute of pumps? How many inputs are available? Can analogue and digital inputs be mixed on the same controller? The answers to these questions help point the user in a certain direction and help refine the lists of potential systems.

Controller outputs are another topic that must be considered. Does the end-user need just digital (on-off, such as with irrigation valve/solenoids), or do they need analogue for things such as pump speed control, pressure control, etc?

There are many more details that must be considered in the selection of a central control system than we can comprehensively address in this paper, but they all need to be identified, considered and evaluated. The results of such an evaluation, as they relate to the system at build-out, will determine which system is correct for the user. Most importantly, if the questions are not asked and the answers not considered appropriately, the user may either purchase a system that is more expensive than is necessary, have more capabilities than is required, or even worse end up purchasing a system that can not be expanded or upgraded to the functionality that the user may require in the future.

Purchasing

For public agencies the procurement process is one in which “low bid” is one of the Achilles heals. However if the user does their homework it does not have to be the trap that everyone thinks it is.

The first step to success is to narrow down your product choices to a reasonable number of makes and models that you feel will meet your needs. Work with the purchasing department to either purchase them for testing or if they indicate that that is somehow against policy they may have a mechanism for vendors to provide them with out charge for testing and then return them to the vendor when testing is complete. Testing will allow you to confirm whether the units do what you require and whether they do what the marketing information claims.

Test for both positive results and negative (i.e. run watering programs and communication with and without power at a remote site and compare the results with what you would expect). Calgary once tested a competitors system and the central indicated that it had successfully irrigated (provided flow data, etc) even though during those days there was no power at the site.

Once complete, the testing will allow you to narrow the field down to models and makes that you are comfortable moving forward with. At that point you write a technical specification for a *Request For Proposal* (RFP) that can only be met by the products that successfully passed the testing. Through the above noted process products have been effectively pre-qualified.

Next is the RFP evaluation process. When evaluating the RFP responses it is important to include a team member who has a demonstrated expertise in automation as it relates to landscape or agricultural irrigation and water management. This same individual or another should also be an expert in telecommunications, particularly wireless. Be certain to build an evaluation system that weights positive technical responses as more important than price. Ensure that all the references submitted by companies answering the RFP are checked. You may be surprised by what you learn and this information could change your decision in a significant way for the good of your organization.

Once you have a central control system the purchasing department will require the contract to be renewed from time to time. They will likely require that a new RFP be sent out to the market place. Ensure that the document captures all the technical specifications and features of your existing system. This should ensure that the new supply contract will continue to supply you with equipment, software and service that are compatible with your existing investments. The last thing any of us would want is a second or third system to operate and maintain.

Installation

Central control systems are not simply “hang on the wall and walk away” systems. They must be installed by technically trained people. The communication system being used to reach the field units will have specific requirements, i.e. is there a communication path between two units on the system that is appropriate for the radio frequency being used? How far is the Ethernet run from the switching center to the units?

Field units (controllers) and computers often will require firmware upgrades, software upgrades and patches, and special settings in the control program depending on what type of communication equipment or path is being followed to get to the field unit. This is often described as system optimization and must be done by factory trained technicians.

Some manufactures/vendors include this in their bids as a matter of policy while others do not and therefore one product can appear to be significantly less costly than another. Once the project is awarded and being installed extras to the contract are requested and the actual price paid for the system becomes significantly greater than the price of all-inclusive system. Such pitfalls can be avoided by ensuring that this is all captured in the original RFP call.

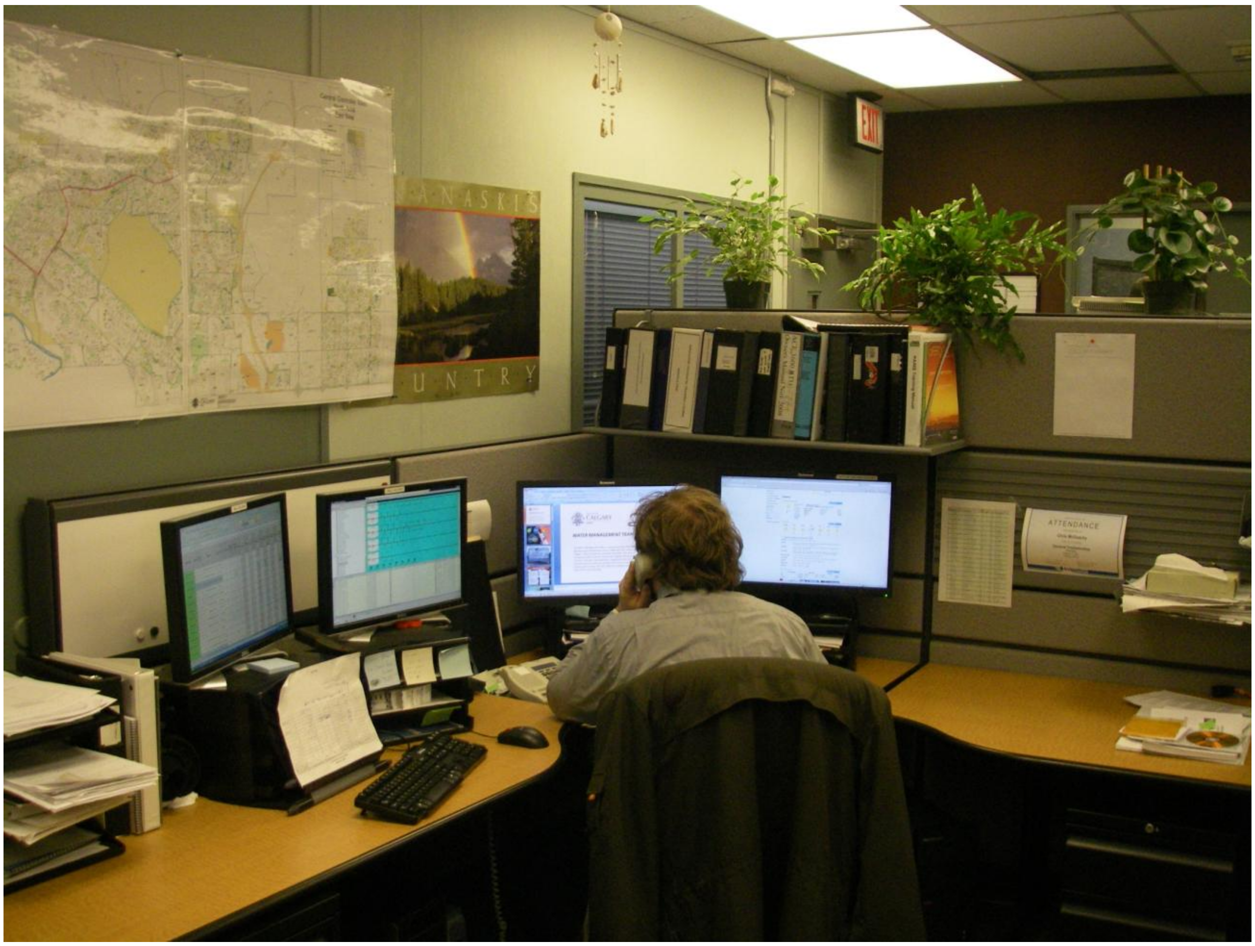
A key point to remember is that installation is specialized work and as such requires people with special skills and training. This costs the vendor money which will be transferred to the project cost. You get what you pay for therefore be aware of the installation requirements when writing and evaluating the RFP.

Operation

One of the most common things users are not prepared for is the operation of a central control system. Marketing literature often claims that the user simply inserts the CD-ROM or other installation media and the system is ready to go. Be wary of comments like “it is as easy as using a word processor”. Chances are if it was really that easy to use it might not really be that effective a control system. Remote control or automation is actual a very complicated and sophisticated field.

Central control systems fall into different categories based on the technologies they use and their methods of communication. They can be relatively simple, more advanced and extremely sophisticated. Which one is right for your application is dependant on the size of the irrigation operation and the future management goals. Some use a single form of communication while others use multiple and mixed forms of communication technologies all simultaneously. There are central control systems that use one-way, two-way, wired, wireless, POTS, TCP/IP, MODBUS, satellite, microwave and other forms of communication.

In order for staff to properly and effectively operate and maintain these systems the central control team must be comprised of people with specialised education, training and experience. They must also receive regular training related to the system that has been purchased and all the technologies that it utilizes as part of its day-to-day operation. Training must also include irrigation training.



At the City of Calgary it was found that employees that had historically worked in irrigation were unable to be trained to a level that ensured their ability to be successful in the operation and maintenance of the system, with a few exceptions. They could not grasp the technical concepts behind the system operation. Because of this The City moved to hiring a new type of employee for the central control group. These people were electronic, computer and telecommunication technicians, computer programmers, and automation and SCADA specialists. With these backgrounds it was easy for them to learn and master the control software and hardware and their post secondary backgrounds made it quite easy for them to learn irrigation principals, master IA education classes and pass IA certification exams.

Opportunities

Despite all the previously noted challenges there are significant benefits associated with implementing a powerful and robust central control system.

The City of Calgary is a great example. Currently Parks has almost 1,200 parks and landscaped areas on its central control system. The central monitors the flows and volumes from over 1,300 water meters (not simply flow sensors) and controls 15,000 valves. With information from six weather stations the central calculates the plant water demand on a daily bases and adjusts the watering times and cycles to replace the lost soil moisture. To accomplish the same level of control and precision the parks department would need to have on staff a minimum of 61 additional staff and vehicles costing over $3,000,000 per irrigation season (May to September). Leak detection and subsequent water turn-off eliminates after hours callouts and saves approximately $500,000 in overtime costs.

Savings also result from the systems ability to detect high flows from broken sprinklers and valves stuck open. Low flows indicate clogged sprinklers and filters. No flow situations are caused by un-opened valves. The central correlates the problem to individual zones and staff arrive on site knowing exactly where to start their repairs rather than having to run through all the zones in order to locate the problem and that reduces troubleshooting and repair time by 75 percent.

Expanded Capabilities

Some of the more advanced and sophisticated central controls can take on non-irrigation roles. These can include lighting control (not just on/off but intensity control), security (such as gate control including ID verification), wetland level control, etc.

In Calgary the parks central control is used to remotely monitor a water recovery, treatment and reuse system for training fire fighters at the City’s Fire Training Academy.

Other uses at The City of Calgary include operating and monitoring storm water irrigation systems that use no potable water for irrigation but instead use rain water that is collected by catch basins in the roadways and is directed to settlement ponds where the water is later used to irrigate sports fields.

Conclusion

Putting in the effort to learn the technical details of central control technology and the different systems being manufactured is worth the return in water, labor and equipment savings that the right system can generate. If time constraints or a lack of specialized expertise are a concern, then the user can hire a specialist in irrigation automation and have the consultant help them acquire the best and most appropriate system for their present and future needs.

Following the concepts and methods discussed here users should be able to avoid the problems and ultimate system failures that many of our peers have faced.

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Control Your Water, Control Your Results: Improving Irrigation Audits and Reducing Soil Hydrophobicity.

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Abstract. *A new, superior irrigation unit and a twenty year old irrigation unit have one thing in common: irrigation audits must be performed regularly to maintain or maximize the benefits of these systems. Enhancing irrigation efficiency and distribution uniformity will allow turfgrass managers to control the water from the irrigation head to below the surface of the soil. As water costs increase, public scrutiny will intensify making the role golf course superintendents and landscape managers crucial for conserving water while enhancing the cosmetic appearance of turfgrass and landscape areas. The objective of this presentation is to review irrigation audit procedures and introduce concepts such as soil water repellency; which may be inhibiting the performance of the irrigation system and reducing turfgrass quality. Soil surfactants will be discussed as tools to improve irrigation efficiency and water distribution in the soil.*

Keywords. irrigation audits, distribution uniformity, irrigation efficiency, soil water repellency, surfactants.

Introduction

It is widely accepted that water conservation laws will be tightened over the next few years due to a growing population and a 10% increase in agricultural withdrawals by 2050 (FAO, 2005). Focus on golf courses and landscape management irrigation practices will be closely monitored, particularly since this land is often designated as recreational land, not critical for water use. Maintaining irrigation system operation is critical to sustain irrigation efficiency and to conserve water use. Despite impressive improvements in irrigation systems and maintaining these systems, soil water repellency may be negatively impacting distribution uniformity.

Soil water repellency (SWR) may be defined as the resistance of soil to wetting and the inability of soil to retain water within the soil profile. The term “hydrophobic” or non-wettable is often used to describe these soils. Soil texture and the water content of soils plays an important role in the development and severity of SWR. Soils with coarse texture – and therefore a smaller surface area – were more prone to SWR then clay soils with larger surface area (Ma'shum et. al., 1988; Cisar et. al., 2000). However, soils with significant amounts of clay (>20%) also exhibited hydrophobicity (McGhie et. al., 1980). Coarser texture soils such as sand do not retain water within the soil profile so extreme wetting and drying cycles occur, exacerbating the water repellent coatings (Miller, 1998). Dekker et. al., (2001) refer to the range between which samples are hydrophilic at upper water content and hydrophobic at the lower content as the "transition zone". If soils are maintained at the higher water content, then soils remain wettable and are easy to re-wet (Dekker et. al., 2001; Wessolek et.al., 2008). Difficulty lies in maintaining soils at the critical water content where organic coatings remain hydrophilic. Golf greens are dried down on an almost daily basis for faster play and to keep the predominantly sand greens from saturation. This daily "dry down" reduces volumetric water content, increases SWR, and therefore LDS and overall poor turf quality is a major issue on greens. To rewet water repellent soils requires significantly more water and defeats water conservation attempts.

Irrigation practices and soil surfactants are effective management tools. It is the objective of this paper to provide information on 1) improving distribution uniformity and irrigation efficiency via irrigation audits and 2) to highlight the success of soil surfactants for ameliorating soil water repellency. Mechanical and chemical management practices are key to water conservation and optimum turfgrass quality.

Irrigation Efficiency

Do you know how effectively your irrigation practices meet turfgrass requirements? Irrigation efficiency determines if you are overwatering and/or underwatering. Improvement of irrigation efficiency promotes turfgrass health and reduces water consumption, electricity and costs. There are three main requirements to improve irrigation efficiency: 1) improve distribution uniformity, 2) reduce irrigation precipitation rates such that it is less than soil infiltration rates and 3) determine field capacity of soil.

Distribution Uniformity

Distribution Uniformity (DU) is a measure of how evenly water is applied by an irrigation system. A DU of > 80% is considered excellent while DU<55% is poor and significant improvements should be made to the irrigation system. Figures 1, 2, 3 and 4 (Courtesy of Rain Bird) illustrate the importance of uniform distribution. The black dashed line is the rootzone and the dark brown area is the wetting front. In Fig. 1, water moves past the rootzone and an uneven wetting front indicates poor irrigation coverage. Water is lost, energy is wasted and high costs are consequences of excessive watering. As illustrated in Fig. 2, poor DU is a consequence of insufficient irrigation. A consequence of underwatering is reduced turf quality. An example of good DU is found in Fig. 3, but irrigation efficiency will be low due to excessive irrigation. Again, the consequence of good DU but poor IE is water waste and higher energy costs. A perfect world is achieved in Fig. 4. Irrigation is evenly distributed and sufficiently wets the rootzone.

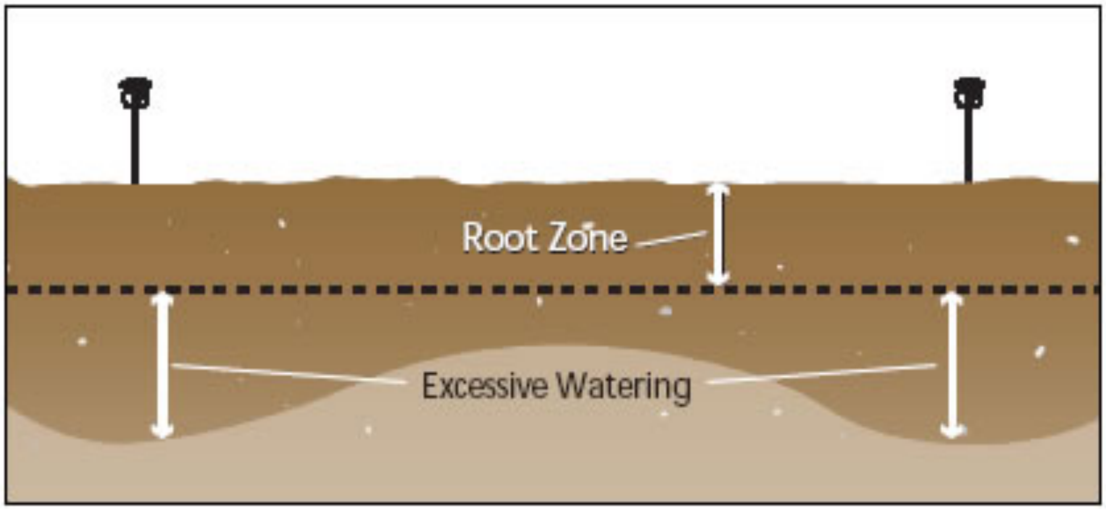

FIGURE 1: Depiction of irrigation resulting in poor DU and excessive watering

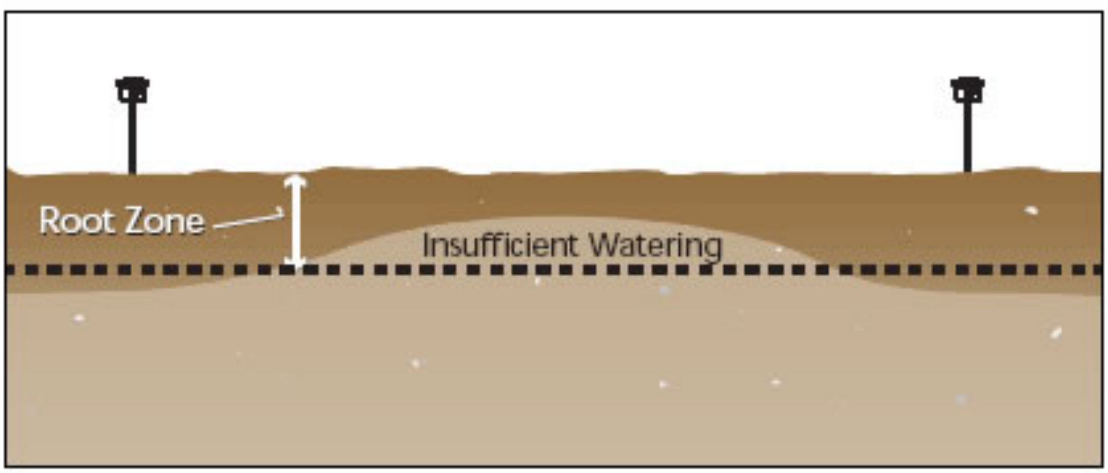

FIGURE 2: Depiction of irrigation resulting in poor DU and insufficient irrigation in parts of the field

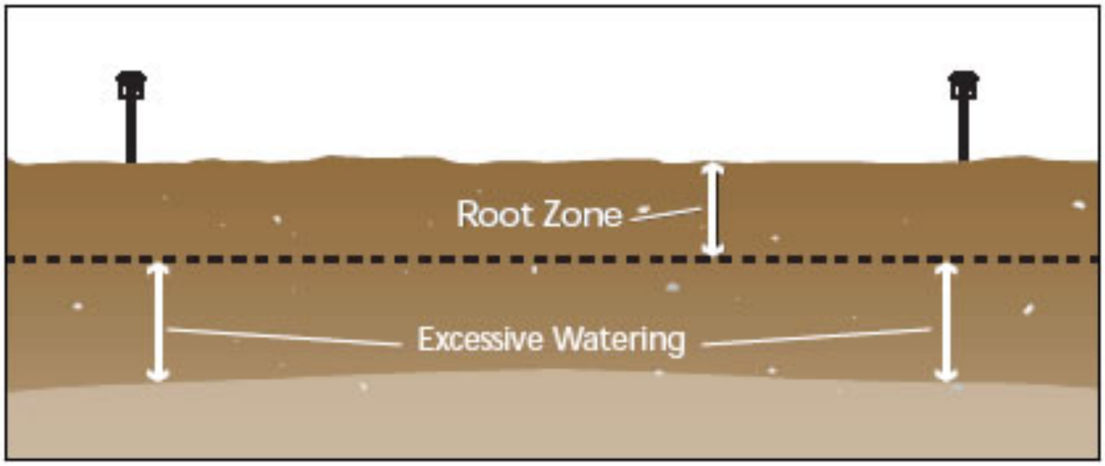

FIGURE 3: Depiction of irrigation resulting in good DU but poor irrigation efficiency

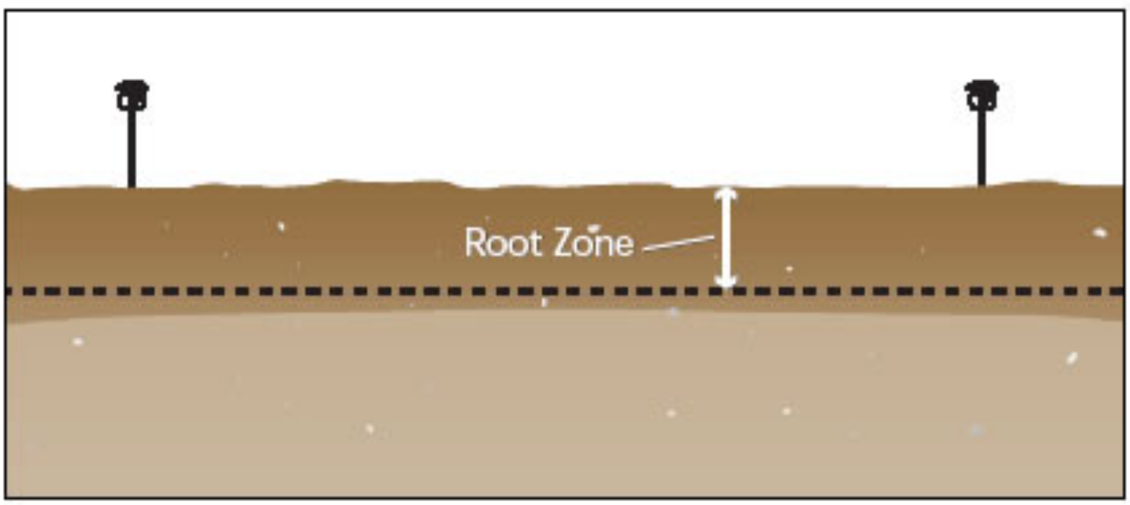

FIGURE 4: Depiction of irrigation sufficiently watering the entire field with good DU and irrigation efficiency

*Figures 1-4 courtesy of Rain Bird.

Method to Determine DU:

An irrigation audit is simple and can be done on your own. Catch containers are placed in an irrigation area (greens – 15 ft. spacing, fairways – 25 ft. spacing). Any type of container can be used; all of them need to be the same size and have the same size opening. Regardless of the area you are measuring, 24 catch containers are necessary to achieve accurate results. Number each container 1-24 with a permanent marker before placing in the test area. Making an overhead "map" of the area and placement of containers will allow you to refer back to the container location for review after you collect and review the data.

After the containers are placed in the area to be tested, run the sprinklers for a set period of time. It is best to run the sprinklers at night, when irrigation is typically applied to the entire course. Collecting water under the same conditions – flow rate and pressures – normally completed provides more realistic data. After the irrigation is run, put the containers in order of water volume from highest to lowest and record this information. Irrigation audit worksheets can be found at the following link: http://s3.amazonaws.com/aquatrols/20120224110212.xls. Add up the total water volume collected, and divide by the total number of catch containers used to determine the average. Now, determine the average volume of the lowest 25% of the catch containers. The lower quarter (LQ) is the weakest area of coverage for the irrigation system (IA. 2003, Kieffer and Huck, 2008).

If the audit results in low DU, there are several things that can be done to improve the number. For example, make sure the irrigation heads are the correct size for the area covered. Are the heads properly and evenly spaced? Check nozzles and replace them if they are worn. If the irrigation system pressure is not correct or the pipes are the not the right size, replace them. DU may be improved by making small changes such as correcting system pressure or replacing worn nozzles. Perhaps irrigation heads or pipes are not the right size and can be fixed. New irrigation systems should also be considered if DU is below <50 %.

Irrigation Precipitation Rate (PR)

Turfgrass managers water based on time, gallons, inches or area. However, it is important to know if the irrigation precipitation rate is less than the soil infiltration rate. If PR is greater than the soil infiltration rate, water will run off or sit on the soil surface and, in hot and dry climates, eventually evaporate. This misleads turfgrass managers into thinking they are applying a certain amount of water when most of it is not infiltrating the soil profile. Data used to calculate DU can also be used to calculate PR. A known PR determines how long to irrigate for a known volume of water.

Method to Determine PR

Measure the mouth of the catch container. If the container used is a square, collect the length (in.) and width (in.) and multiply together for the total of the container mouth. Record the test run time in minutes. Multiply the average volume of the containers (determined in DU calculations) and multiply by 3.66 (ml/min to in/hr. conversion factor);

this will be number 1. Multiply by the total run time by the area of the container mouth; this will be number 2. Divide number 1 by number 2. The result is your PR (in/hr.) (Kieffer and Huck, 2008).

Field Capacity

Field Capacity (FC) is the water holding capacity of the soil and is defined as the amount of water held in soil against the force of gravity. To determine FC, saturate the soil and then allow one day for the gravitational water to drain. Take soil moisture measurements using a moisture meter and determine the percent volumetric water content. This will be your FC. Wilt point (WP) is the amount of water that is not available for plant use (Brady and Weil, 2008). WP is determined by collecting soil moisture measurements when turfgrass begins to wilt. Collecting FC and WP will identify turfgrass areas which may need supplemental irrigation, but Kieffer and Huck, (2008), determined that DU calculated via soil moisture data rather than the catch can method would be higher. Handwatering turfgrass areas and then determining soil moisture via moisture meter probe assesses handwatering practices and measures soil moisture – also a good measure of DU of irrigation systems. It is important to remember that FC varies from one area to another, sometimes substantially. Therefore, it is important to use the same meter for every measurement and collect many measurements over the irrigated area.

Soil Water Repellency (SWR)

The cause of SWR is the hydrophobic organic coatings on soil and sand particles (Schreiner and Shorey, 1910). These non-polar, hydrophobic coatings surround the soil particle and prevent water, a polar molecule, from attaching to the soil surface. The origin of SWR is as varied as its distribution. Sources of organic acids which contribute to SWR are numerous (Fig. 5). Plant root exudates, fungal exudates and decomposing plant materials are just a few of the sources that contribute to the organic acid deposition on soil particles. Water repellent coatings influence water movement by decreasing water infiltration at the soil surface, and minimizing uniform water penetration throughout the soil profile (Fig.6). Effectiveness of irrigation systems is diminished by SWR. A perfect irrigation system may place a water drop exactly where it needs to go, but SWR prevents permeation of that water drop.

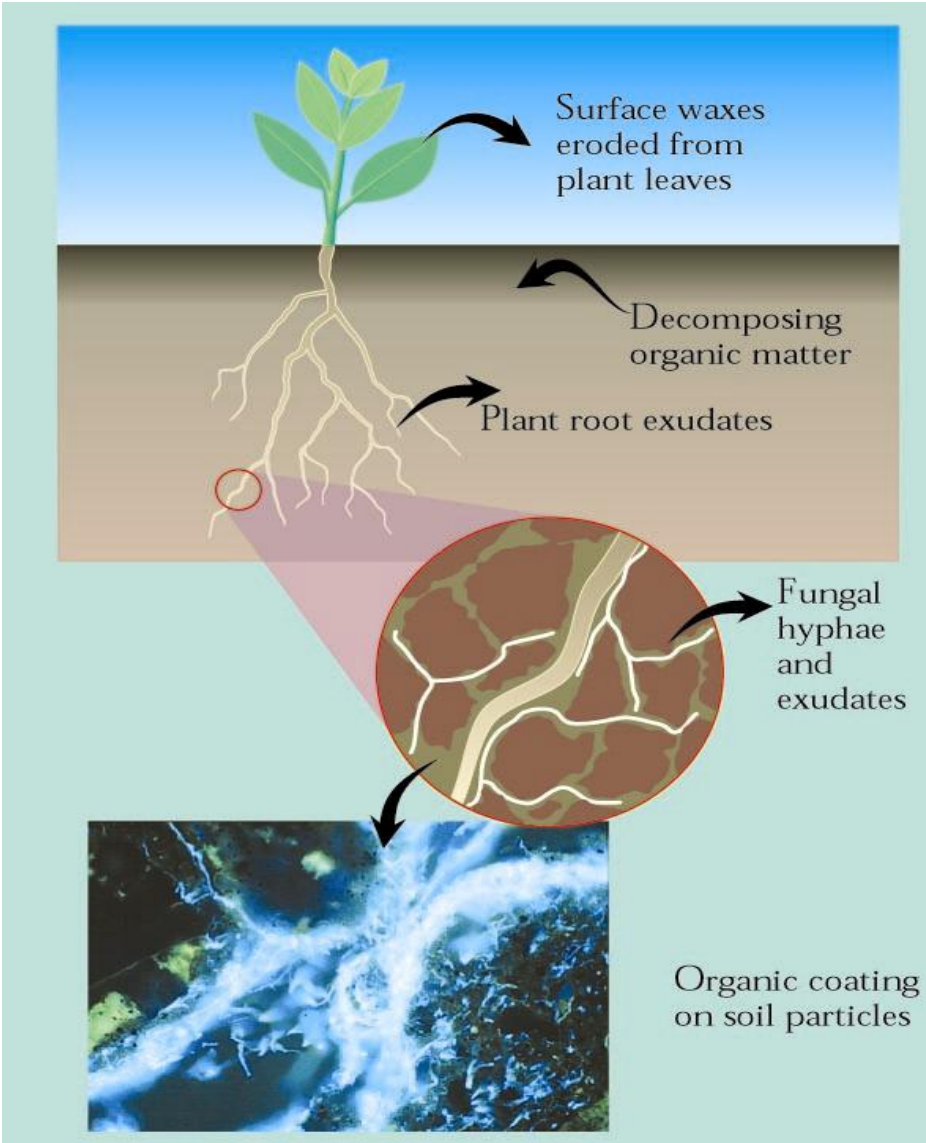

Figure 5. Sources of organic acids. Courtesy of Paul Hallett, Scottish Crop Research Institute

How to Determine Soil Water Repellency

Soil water repellency is determined by a water drop penetration test (WDPT) (Letey, 1969). Using a soil probe, collect a soil sample and air dry at room temperature for two weeks. Soil must be completely dry to determine degree of soil water repellency. Place a water droplet, using a straw or pipette, at one cm intervals along the soil core as exhibited by Fig. 6. Time how long the soil core takes to move into the soil core.

Figure 6. WDPT conducted on a soil core. Photo courtesy of Demie Moore.

Severity of soil water repellency may be determined using Table 1. The more severe the soil hydrophobicity, the more difficult soils are to rewet. Difficulty rewetting soils precedes poor turf quality.

Table 1. Soil Water Repellency Classification. (Ritsema and Dekker, 1996)

WDPT time (sec)	Classification
< 5	Wettable
5-60	Slightly Water Repellent
60-600	Strongly Water Repellent
600-3600	Severely Water Repellent

Surfactants

To minimize the effects of SWR, soil surfactants are applied via irrigation systems. Surfactants are molecules with a hydrophilic end to attract water and a hydrophobic end to attach to hydrophobic coatings on soil particles. Surfactants work in two ways: 1) by reducing surface tension at the soil-air interface and 2) coating hydrophobic soil particles to create hydrophilic particles. Reducing surface tension at the soil-air interface improves water infiltration and reduces runoff.

Field Trial #1

Research was conducted by Nuno Bobone Sepulveda at Ohio State University in Wooster, Ohio in 2004. *L93* bentgrass was established on a silt loam soil with a 4% slope and maintained as a golf course fairway. Plots were arranged in a complete randomized block design with three replicates. Runoff was collected at the end of the slope using a tipping bucket flow meter with a flume. An APG-E soil surfactant was injected weekly through an irrigation system at a rate of 1.74 L/ha. Runoff measurements were collected during rainfall events on 4 different days. Data was collected as the number of tippings that occurred after four rainfall events and the mean average was determined. Data presented in Figure 7, reveals significant reduction in runoff in the surfactant treated plots (Sepulveda, 2004). Reduced runoff enhances DU and improves irrigation efficiency.

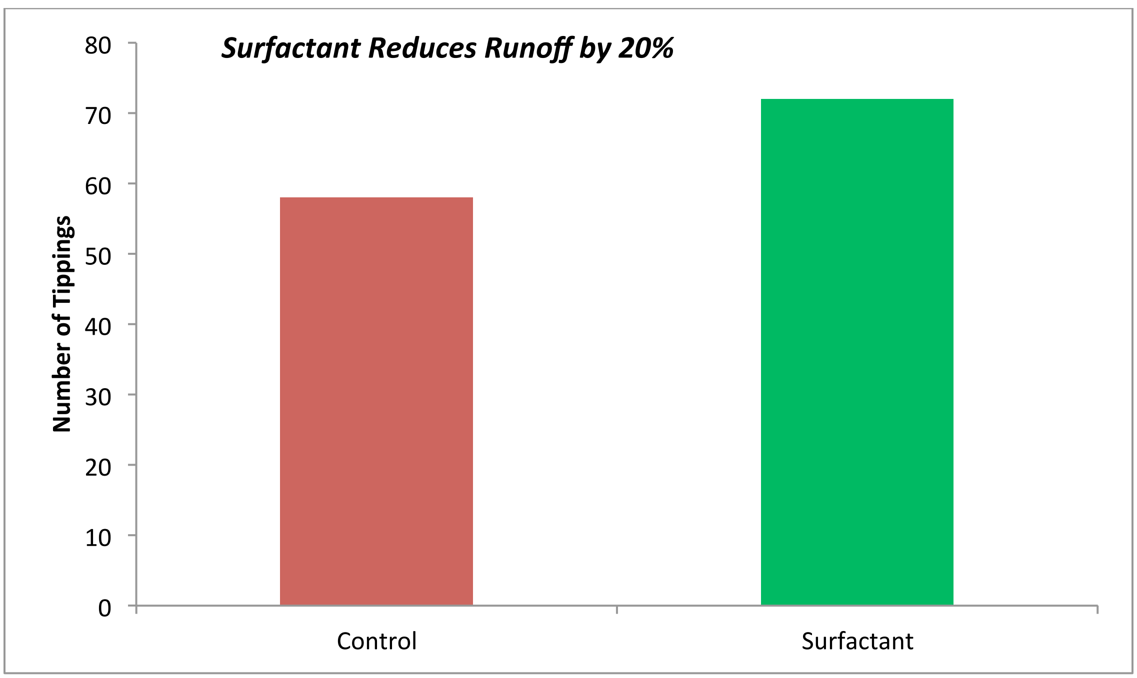

Fig. 7. Surfactant plots significantly reduced runoff. Research conducted at Ohio State University, Wooster, 2004.

Field Trial #2

SWR in the soil profile creates preferential or “finger” flow paths (Fig. 8). Wettable soil particles create matrix flow of water through the profile. Generally, soil surfactants hydrophilize soil particles and increase volumetric water content of soils. A research project was conducted at the Center for Turf Irrigation and Landscape Technology, at California State Polytechnic University, Pomona, California in 2003 and 2004. Bermudagrass plots grown in a clay loam soil and maintained as a golf course fairway were laid out in a split plot design with three replicates.

While irrigation water quality (potable and recycled) was the main factor, a soil surfactant was also evaluated. An APG-E soil surfactant was applied every week at a rate of .877 L/ha. In the first month of the trial, plots were irrigated at 100% reference cumulative evapotranspiration rates (ET_0) in the first month. ET_0 was reduced to 70%, 30% and 10% over the next 3 months, respectively. Volumetric water content was collected at 150 mm depth using time domain reflectometers. Data presented in Table 2 is the average of percent volumetric water content collected on the 15th day of every month during the trial. Surfactant treatment significantly increased VWC when compared to the control treatment (Mitra, et al., 2005). By enhancing uniform water flow throughout the soil profile, DU is maximized and all chemicals applied with surfactants are evenly distributed, enhancing turfgrass quality.

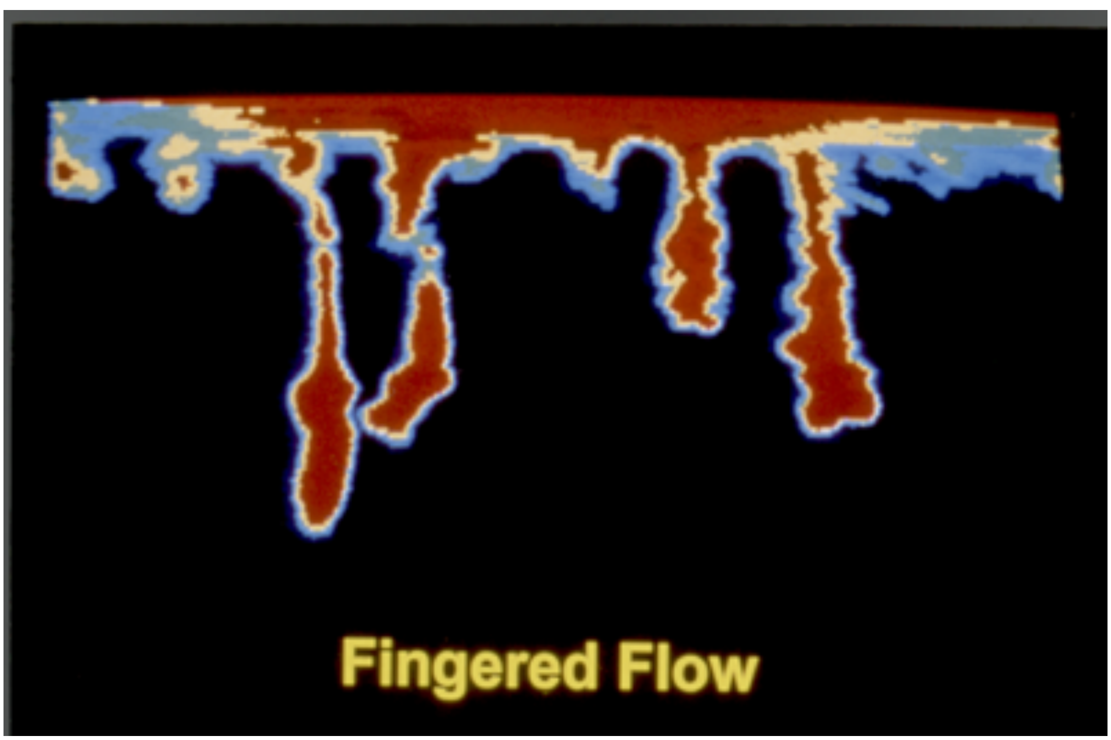

Figure 8. Preferential Flow Paths. Figure courtesy of Tammo Steenhuis, Cornell University.

Table 2. Effect of an APG-E soil surfactant on volumetric soil moisture (VWC) (%) content in soils.

Treatments	Volumetric Soil Water Content (%)							
	100% ET		70% ET		30% ET		10% ET	
	Potable	Recycled	Potable	Recycled	Potable	Recycled	Potable	Recycled
ACA1848	56 a*	58 a	36 a	35 a	29 a	32 a	28 a	27 a
Untreated	46 c	40 c	28 c	28 c	18 d	22 c	16 c	17 c

*The means followed by the same letter do not significantly differ. (P = 0.05 Duncan's New Multiple Range Test).

Conclusion

Distribution Uniformity is strongly influenced by soil water repellency. Soil surfactants are proven tools to mitigate soil water repellency and conserve water while enhancing turfgrass quality. Superior irrigation systems are only as effective as the wettability of your soil. By incorporating irrigation audits and soil surfactants into your turfgrass management practices, optimum DU is possible and the overall goal of water conservation is achieved.

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Irrigation Management System, IMANSYS, a User-Friendly Computer Based Water Management Software Package

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Abstract

The IMANSYS model is an irrigation water requirements (IWRs) calculation model; it is an altered form of the agricultural field scale irrigation requirements simulation (AFSIRS) model (Smajstrla and Zazueta, 1988). It calculates runoff, drainage, canopy interception, and effective rainfall based on plant growth parameters, soil properties, irrigation system, and long-term weather data (rain, evapotranspiration, and temperature). IWRs are calculated based on different water management practices. IMANSYS calculates evapotranspiration based on temperature data using different models. IMANSYS has several databases of, e.g., soil and plant growth parameters, irrigation systems, canopy interception. IMANSYS was implemented in JAVA object oriented language. IMANSYS output includes detailed net and gross IWRs, and all water budget components at different time scales (daily, weekly, biweekly, monthly, and annually) based on non-exceedance drought probability which is calculated from a conditional probability model that uses the type I extreme value distribution for positive non-zero irrigation values.

Introduction

Plant water requirement is the amount of water, in addition to rainfall, that must be applied for a particular crop to meet its evapotranspiration needs and maintain optimum yield. It is usually called also net irrigation requirement (IRR_{net}) which is the irrigation water that is delivered to the rootzone and available for the plants to use. Estimates of irrigation requirements can be made based on site specific historical irrigation data or calculated using mathematical models. The latter method may be based on statistical methods or on physical laws which govern crop water uptake and use. Effective rainfall is that portion of rainfall which can be effectively used by a plant, that is, rain which is stored in the plant root zone. Therefore, effective is less than total rainfall due to canopy interception, runoff and deep percolation (or drainage) losses. A plant's irrigation requirement, as defined here, does not include water applied for freeze protection, crop cooling, or other purposes, even though water for these purposes is required for crop production and is applied through irrigation systems.

Estimates of irrigation requirements calculated using mathematical models use water budget models to historical climate data to obtain historical irrigation water demand. Water budget model refers to the accurate tracking of inputs, outputs, and soil water storage of an irrigated system. Water budget components include rainfall, irrigation, drainage below the root zone, runoff, canopy interception, evapotranspiration, and changes in soil water storage. These water budget models have been used for irrigation scheduling and crop water requirement estimation (Smajstrla, 1990; Obreza and Pitts, 2002; Fares et al., 200). Smajstrla (1990) developed the Agricultural Field Scale Irrigation Requirements

Simulation (AFSIRS) model that uses a water balance approach with layered soil column to simulate soil water infiltration, redistribution, and extraction by evapotranspiration as steady state processes on a daily basis. The AFSIRS model simulates the irrigation requirements for a crop based on plant physiology, soil, irrigation system, growing season, climate and basic irrigation management practice. The AFSIRS does not account for runoff and canopy interception and it cannot simulate multiple crops. It was designed for Florida's soils and crops.

The main goal of this paper is to give a detailed overview of the newly developed Irrigation water Management System, IManSys, model. IManSys is an irrigation water requirements (IWRs) calculation model; it is an altered form of the agricultural field scale irrigation requirements simulation (AFSIRS) model (Smajstrla and Zazueta, 1988).

Model description

Irrigation Management System (IMANSYS)

IManSys is a Microsoft Windows based model that calculates irrigation requirements for regional crops on daily, weekly, monthly, and annual basis. Model also offers flexibility to add additional crops or modify the information about existing crops. The irrigation requirement from specific plants is calculated based on extreme value frequency analysis on long-term daily irrigation estimates. Detailed description of the model and its components are present below.

Water Budget in IMANSYS

Similar to AFSIRS, IMANSYS model uses the water balance approach with a two-layer soil profile to simulate the irrigation water requirement for specific plants on a daily basis. The plant specific irrigation requirements are calculated based on plant physiology, soil, irrigation system, growing season, climate and basic irrigation management practice. The daily water balance equation for the soil column defined by the crop root zone expressed in terms of equivalent water depth per unit area (cm) is:

$$\Delta S = P + G + IRR_{net} - (Q_D + Q_R + ET_c + I) \qquad (1)$$

where ΔS is the change in soil water storage expressed as equivalent water depth (cm), P is the gross rainfall (cm), G is the groundwater contribution (cm) from shallow water table, IRR_{net} is the net irrigation requirement (cm), (Q_D + Q_R) is summation of groundwater drainage and surface water runoff (cm), ET_c is the plant evapotranspiration (cm), and I is canopy rainfall interception (cm). The water storage capacity (S) is amount of water that is available for plant uptake (cm). It is calculated as the equivalent water between field capacity and permanent wilting point for a given soil multiplied by the depth of the root zone.

The soil profile depth was assumed to be equal to the crop root zone depth. The plant root zone was divided into irrigated (upper 50 %) and non-irrigated (lower 50 %) zones based on the common practice of irrigating only the upper portions of the crop root zone where most of the roots are located (Smajstrla, 1990; Smajstrla and Zazueta, 1988). It is assumed that 70 and 30% of crop ET is extracted from these zones, respectively, when water is available (SCS, 1982). This pattern of water extraction is typically assumed for well-irrigated plants on non-restrictive soil profiles (Smajstrla and Zazueta, 1988).

Rainfall and canopy interception

Gross rainfall measured above canopy was adjusted with user defined canopy interception factor. If interception fraction is not available, model calculates it based on leaf area indices (LAI) and plant height (H) as described by Rutter et al. 1975. The basic interception calculation follows the following conditions:

$$I = I_{max} \quad \text{if } P >= I_{max} \qquad (2a)$$

$$I = P \quad \text{if } P < I_{max} \qquad (2b)$$

Where I is daily interception, Imax is the maximum daily interception calculating using the methods described below, P is the daily rainfall

During irrigation period, daily LAI value is obtained by the following equations:

$$LAI = K_c/K_{cmax} * LAI_{max} \quad \text{Perennial Crop} \qquad (3a)$$

$$LAI = DRZI/DRZI_{max} * LAI_{max} \quad \text{Annual Crop} \qquad (3b)$$

And interception is calculated as:

$$I_{max} = 0.2 * LAI \text{ (mm)} \qquad (4)$$

Method based on plant height is only available for annual crops, using the following equation to obtain LAI to calculate interception using equation (2):

$$H = DRZI/DRZI_{max} * H_{max} \qquad (5a)$$

$$LAI = 24H \qquad (5b)$$

Where DRZI and $DRZI_{max}$ are the initial and maximum root zone depth for annual and perennial crops; K_c and K_{cmax} are the initial and maximum crop water use coefficients, respectively.

After subtracting the canopy interception, soil water contents are adjusted based on net rainfall (Gross rainfall-canopy interception). If effective rainfall (net rainfall-surface runoff) amount is sufficient to exceed field capacity in the irrigated root zone, the excess is added to the non-irrigated root zone. For micro irrigation systems, where the entire soil surface is not irrigated, rain is also added to the non-irrigated root zone, in proportion to the non-irrigated surface area.

Reference Evapotranspiration

IMANSYS provides options to select the appropriate model for ET calculation if the ET data is not available for the area. These ET models include the Hargreave-Samani (1985), the Evapotranspiration Prediction Model (ETM) based on Priestley-Taylor as detailed by Fares (1995), the FAO56-PM method (Allen et al., 1998).

Surface Runoff

Surface runoff (Q_R) was calculated using SCS curve number method (SCS, 1985 and 1993) using the following equation:

$$Q_R = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (6)$$

where P is daily rainfall (cm), S is potential maximum retention (cm) which is related to SCS curve number as:

$$S = \frac{2540}{CN} - 25.4 \qquad (7)$$

CN is the curve number which is related to the imperviousness of the surface. CN was determined based on hydrologic soil group and land use type.

Drainage

Drainage (Q_D) is the portion of rainfall in excess of rain stored in the soil profile to field capacity or depleted by crops (ET_c) as the water is redistributed in the soil. Drainage is calculated for days on which rainfall occurs and the amount of rain exceeds the soil water-holding capacity. When that occurs, the water which is percolating through the profile, is considered to be effective until redistribution to field capacity has occurred. Drainage from the irrigated and non-irrigated zones is calculated as the amount of water which is in excess of that required to restore the root zone to field capacity and to provide crop ET while it is redistributing. Drainage from these zones leaves the entire crop root system as leaching or groundwater recharge.

Gross Irrigation Requirement (IRR)

Irrigations were assumed to start when the available water for plant uptake decreases to a predetermined minimum allowable level, termed allowable soil water depletion (AWD) percentage. AWD values were determined from the literature and are fractions of the available soil water storage capacity that can be allowed to be depleted without significant reduction in crop yield. AWD values for the annual and perennial crops are user specific and can be provided with crop information. Model uses AWD 0.50 as default for all perennial crops. A value of 0.50 means that 50% of the available water in the irrigated crop root zone is allowed to be depleted between two consecutive irrigation events.

The irrigation requirement is calculated as the depth of water required to replenish the soil water content to field capacity in the irrigated crop root zone. Water losses occurred during irrigation due to irrigation system efficiencies were also added into irrigation requirements (i.e., gross irrigation water demand) by dividing IRR with a coefficient of irrigation system efficiency (f_i). The value of f_i varies with irrigation type between zero and one. The gross irrigation requirement (IRR) was calculated for each crop using the following equation, which is derived from Eq. (1):

$$IRR = \frac{ET_c - (P - Q_R - Q_D - I)}{f_i} \qquad (8)$$

where f_i is the irrigation efficiency.

Statistical Analysis of IRR

Statistical analysis is performed on calculated IRR on weekly, bi-weekly, and monthly time steps based on long-term climate data. In addition to mean, median, minimum, maximum, and coefficient of variation of IRR, model also calculates IRR at 50%, 80%, 90%, and 95% using the least square fit to type 1 extreme value distribution. A 50% probability IRR will be expected to exceed once in every two years and if the data follows the normal distribution, 50% IRR will be equal to mean value. All the calculations were based on the methodology presented by James et al. (1983).

Materials and Methods: Case Study

Study Area

Irrigation requirements were estimated for ten locations across the state of Hawaii located between 18° 55′ N and 28° 27′ N latitude and 154° 48′ W and 178° 22′ W longitude. The study locations by island were: East Kauai, Kauai Coffee and Kekaha in Kauai Island; Waiahole and Waimanalo in Oahu Island; West Maui and Upcountry Maui in Maui Island; Molokai in Molokai Island; and Lower Hamakua and Waimea in Hawaii (Big) Island (Figure 1).

Crop Selection

In this study, 22 annual crops (Table 1a) and 11 perennial crops (Table 1b) that have high value for Hawaiian agricultural industry were selected. Irrigation requirements for all of the 33 crops were estimated for ten locations scattered on the Hawaiian Islands. The root zone information for the selected crops used in this study is provided in Table 1. The crop root zone for perennial crops was assumed to be constant. The crop root zone development for annual crops has four growth stages. The average growth stage lengths differ by crop and are given as fractions of the crop growing season. The root zone was held constant at the minimum depth throughout crop growth stage 1 that is crop establishment period. The root zone increases linearly to a maximum depth throughout growth stage 2 that is vegetative growth and development period. The maximum root zone is attained at the beginning of crop growth stage 3, which is peak of the growth period, and is maintained throughout growth stages 3 and 4. Growth stage 4 is the period of a crop from maturity to harvest (Smajstrla, 1990).

Soil

Representative soil series, textures, and water-holding capacities for each location were identified with the USDA Soil Survey of the State of Hawaii and supporting documents (USDA 1972; USDA, 1979). The water storage capacity within the crop root zone was defined as the product of the available water-holding capacity of the soil (Table 2), and the depth of the effective root zone for each crop (Table 1a and 1b).

Meteorological Data

Historical long-term daily rainfall data were obtained for stations within each system from the National Climate Data Center (NCDC) on-line database at http://www.ncdc.noaa.gov/oa/climate/climateinventories.html. Daily minimum and maximum temperature data was also downloaded from NCDC for Waimanalo and Upcountry Maui stations**.** Climate station location and climatic information are presented in Table 3.

Irrigation Requirement Calculations

IRR for annual crops were calculated for wet season (October to February) and dry season (April to August) whereas for perennial crops, they were calculated for the whole year. Hereafter the wet season will be referred as season-1 and dry season as season-2. Irrigations were assumed to start when the available water for plant uptake decreases to a predetermined minimum allowable level, termed allowable soil water depletion (AWD) percentage. AWD values were determined from the literature and are fractions of the available soil water storage capacity that can be allowed to be depleted without significant reduction in crop yield. AWD values for the annual crops used in this study are given in Table 1a whereas an AWD value of 0.50 was used for all perennial crops. A value of 0.50 means that 50% of the available water in the irrigated crop root zone is allowed to be depleted between two consecutive irrigation events.

Irrigation Systems

Drip and micro-sprinkler were the irrigation system types selected for most crops, with the former assigned primarily to vegetable crops and the latter to fruits and other perennials. Other irrigation system types assigned were; multiple sprinklers for alfalfa and lettuce, sprinkler–large guns for bana grass, and flood irrigation for taro. Irrigation system efficiency was assumed to be 85, 80, 70, 50, and 30 % for drip, micro-sprinkler, multiple sprinklers and sprinkler–large guns, flood, and nursery container irrigation systems, respectively (Tables 1a and 1b).

RESULTS AND DISCUSSIONS

Orthographic lifting and subsequent cooling of the moisture laden trade winds are the primary rainfall-producing mechanism over the islands. This results in substantially less rain on the leeward side due to a rain shadow effect. As a result, water deficits relative to potential ET are greater on the leeward, relative to the windward, sides of the Islands. At a single location, there is a significant temporal rainfall variability from month to month (Figure 2). In most of the location, rainfall maxima and minima occur in January and June, respectively. The difference between winter maxima and summer minima are greatest in dry areas, while wet areas are characterized by two peaks in precipitation throughout the year (Figure 2). At both Waiahole and Waimanalo, January and November were the wettest month. Spatial variability in rainfall occurs not just across mountain ranges and between islands, but also within individual watersheds and is primarily influenced by topography. In the Kauai Coffee, a gradient of approximately 122 m in the direction of mountains to ocean results in a difference of 1 m of rainfall (with little difference in ET).

The calculated IRR values differed temporally and spatially between locations due to the rainfall variation that occurs on each island. Climate station location and climatic information are presented in Figure 1 and Table 3. Historical annual rainfall is the lowest in the Waimea, West Maui, Waiahole, and Kekaha locations (42.9, 49.3, 52.8, and 54.1 cm, respectively) and highest in the East Kauai and Lower Hamakua systems (186.7 and 241.1 cm, respectively). ET_o data has less variability among systems than rainfall (ranging 120.6- 239.3 cm annually), and is generally inversely related to rainfall. Deficits between annual rainfall and potential ET were greatest in the West Maui and Molokai systems, averaging about 147.3 cm less rainfall than potential ET. The Lower Hamakua and East Kauai systems have clear water excess as they receive more annual rainfall than water losses through ET (78.7 and 38.1 cm more, respectively).

Hydrographically, the islands can be characterized into windward and leeward sides with the windward receiving significantly more rainfall compared to the leeward side. As a result, for both annual and perennial crops windward needs less IRR compared to leeward (Figure 3). Irrigation requirement for both annual and perennial crops at Waiahole, located in the leeward side is almost double as compared to Waimanalo which is located in windward side (Figure 3). IRR varies with the wet season (October to February) requiring less water and the dry season (April to August) requiring more. Variation in irrigation water requirement can vary not only with locations, but also with crops. For sweet corn the water budget component between two seasons are presented in Figure 4A and Figure 4B. Irrespective of location the mean, minimum, and maximum IRR can be more than double during summer season as compared to winter season. This difference is mostly due to low rainfall and higher ET during summer months as compared to winter.

IRR requirement for selected annual and perennial crops are presented in Figure 5. Water requirement for pineapple is significantly lower but it can vary from one location to another. The IRR requirements for some crops can be 4 to 5 times higher between one location to another. Irrespective of crop type, IRR for East Kauai was lowest among all twelve stations and Molokai had the highest (results not shown). For the same crops Dendrobium and Draceana, IRR varied significantly due to difference in irrigation system type (micro-spray vs nursery sprinkler). The IRR calculations show some crops needs less water such as pineapples than others, and some crops such as taro, need more water than any other crops within a single location. The IRR requirement varies with location, planting periods and crop types. Therefore, if a water thirsty crop is planted in wet season and a plant with less water requirement is planted in the following dry season, a considerable overall cost reduction in irrigation water requirement can be obtained.

In Hawaii seed corn can be grown any time during the due to suitable climatic condition throughout the year. When IRR requirement was compared with different sowing date, May and November, resulted in highest and lowest IRR, respectively (Figure 6). IRR for seed corn sown in May is 2.5 times higher than that of sown in November. This variably is consistent with the monthly variability in rainfall and ET during the year.

SUMMARY AND CONCLUSION

This manuscript summarized the main steps of the development the Irrigation Management System (IManSys) software which uses weather, soil and crop databases, e.g., daily rainfall and evapotranspiration, soil physical properties, irrigation system characteristics, and crop parameters to calculate site and plant specific irrigation requirements. IManSys is proven to be a reasonable management tool, an effective teaching software for different users. This package might require several modifications to allow it use in different environment and help answer multiple questions.

ACKNOWLEDGMENTS

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Table 1a: Annual crop Kc values and stage lengths as a fraction of growing period

Crop	Root depth (cm)		Crop Kc			Duration (fraction of crop cycle)				Allowable water depletion (fraction of total)				Irrigation type*	Irrigation efficiency (%)
	Irrigated Depth	Total Depth	$Kc_{initial}$	Kc_{mid}	Kc_{late}	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4		
Alfalfa, initial	20.32	60.**96**	0.4	0.95	0.9	0.14	0.38	0.31	0.17	0.5	0.5	0.5	0.5	S	70
Alfalfa, ratoon	60.96	60.96	0.4	0.95	0.9	0.14	0.38	0.31	0.17	0.5	0.5	0.5	0.5	S	70
Banana, initial	60.96	121.92	0.5	1.1	1	0.31	0.23	0.31	0.15	0.35	0.35	0.35	0.35	MS	80
Banana, ratoon	121.92	121.92	1	1.05	1.05	0.33	0.16	0.49	0.01	0.35	0.35	0.35	0.35	MS	80
Cabbage	20.32	30.48	0.7	1.05	0.95	0.24	0.36	0.3	0.09	0.45	0.45	0.45	0.45	D	85
Cantaloupe	20.32	30.48	0.5	0.85	0.6	0.08	0.5	0.21	0.21	0.35	0.35	0.35	0.35	D	85
Dry Onion	20.32	30.48	0.7	1.05	0.75	0.1	0.17	0.5	0.23	0.25	0.25	0.25	0.9	D	85
Eggplant	20.32	30.48	0.7	1.05	0.9	0.21	0.32	0.29	0.18	0.4	0.4	0.4	0.4	D	85
Ginger	20.32	30.48	0.7	1.05	0.75	0.1	0.17	0.5	0.23	0.25	0.25	0.25	0.25	D	85
Lettuce	20.32	30.48	0.7	1	0.95	0.2.7	0.4	0.2	0.13	0.3	0.3	0.3	0.3	S	70
Other melon	20.32	30.48	0.5	1.05	0.75	0.21	0.29	0.33	0.17	0.35	0.35	0.35	0.35	D	85
Pineapple, yr1	30.48	30.48	0.5	0.3	0.3	0.16	0.33	0.26	0.25	0.6	0.6	0.6	0.6	D	85
Pineapple, yr2	60.96	60.96	0.3	0.3	0.3	0.38	0.32	0.27	0.03	0.6	0.6	0.6	0.6	D	85
Pumpkin	20.32	30.48	0.5	1	0.8	0.2	0.3	0.3	0.2	0.35	0.35	0.35	0.5	D	85
Seed Corn	30.48	45.72	0.4	1.2	0.5	0.16	0.28	0.32	0.24	0.6	0.6	0.6	0.8	D	85
Sugarcane, New- year 1	45.72	91.44	0.4	1.25	1.25	0.21	0.29	0.25	0.25	0.65	0.65	0.65	0.65	D	85
Sugarcane, New- year 2	91.44	91.44	1.25	1.25	0.75	0.14	0.14	0.14	0.59	0.65	0.65	0.65	0.65	D	85
Sugarcane, ratoon	91.44	91.44	0.4	1.25	0.75	0.1	0.15	0.46	0.29	0.65	0.65	0.65	0.65	D	85
Sweet potato	20.32	30.48	0.5	1.15	0.65	0.12	0.24	0.4	0.24	0.65	0.65	0.65	0.65	D	85
Taro	20.32	30.48	1.05	1.15	1.1	0.2	0.13	0.4	0.27	0	0	0	0	F	50
Tomato	20.32	30.48	0.6	1.15	0.8	0.2	0.27	0.34	0.19	0.4	0.4	0.4	0.65	D	85

Watermelon	20.32	30.48	0.4	1	0.75	0.15	0.26	0.26	0.32	0.26	0.32	0.26	0.32	D	85

* MS = micro spray, NS = nursery sprinkler, S = Sprinkler, D = Drip, F = Flood

Table 1b: Perennial crop effective root depth Kc values by month of the year.

Crop	Root depth (cm)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Irrigation type*	Irrigation efficiency
	Irrigated Depth	Total Depth														
Coffee	60.96	121.92	0.85	0.85	0.85	0.9	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	MS	0.8
Dendrobium,	20.32	20.32	1	1	1	1	1	1	1	1	1	1	1	1	MS; NS	0.80, 0.20
Draceana, pot	20.32	20.32	1	1	1	1	1	1	1	1	1	1	1	1	MS; NS	0.80, 0.20
Eucalyptus closed canopy	182.88	182.88	1	1	1	1	1	1	1	1	1	1	1	1	MS	0.8
Eucalyptus young	121.92	182.88	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	MS	0.8
Guava	76.2	152.4	8	0.9	1	1	9	0.8	0.8	0.9	1	1	9	8.5	MS	0.8
Heliconia	60.96	121.92	1	1	1	1	1	1	1	1	1	1	1	1	MS	0.8
Kikuyu grass	60.96	121.92	1	1	1	1	1	1	1	1	1	1	1	1	S	0.75
Lychee	76.2	152.4	0.95	1	1	1	0.95	0.9	0.9	0.85	0.8	0.8	0.9	0.9	MS	0.8
Macadamia nut	76.2	152.4	0.85	0.85	0.85	0.9	0.95	0.95	0.95	0.95	0.95	0.95	0.9	0.9	MS	0.8
Ti	60.96	121.92	1	1	1	1	1	1	1	1	1	1	1	1	MS	0.8

* MS = micro spray, NS = nursery sprinkler, S = Sprinkler

Table 2. Representative soils for each of the ten target locations.

Location	Weather Station	Soil series	Texture	Water holding capacity (cm^3 cm^{-3})
East Kauai	Lihue Variety	Kapaa	Silty clay	0.14
Kauai Coffee	Wahiawa	Makaweli	Stony silty clay loam	0.15
Kauai Coffee	Brydswood	Koloa	Stony silty clay	0.11
Kekaha	Kekaha	Kekaha	Silty clay	0.105
Kekaha	Mana	Lualualei	Clay	0.115
Waiahole	Kunia.Sub	Kunia	Silty clay	0.13
Waimanalo	Wai.Exp.Sta	Waialua	Silty clay	0.14
Molokai	Kaunakakai	Molokai	Silty clay loam	0.12
West Maui	Pohakea	Pelehu	Clay loam	0.13
Upcountry	Kula	Kula	Loam	0.14
Waimea	Lalaumilo	Waimea	V. fine sandy loam	0.14 at 0-1.27 m 0.02 at 1.27-2.29 m
Lower Hamakua	Paauilo	Paauhau	Silty clay loam	0.14 at 0-1.27 m 0.06 at 1.27-2.29 m

Table 3: Climate stations and characteristics of the ten target locations.

ID	Location	Climate Station	Island	Latitude	Longitude	---------Rain----- Years of record	Annual mean (cm)
1	Kekaha	Mana	Kauai	22.04	-159.77	(1950-95)	72.1
2	Kekaha	Kekaha	Kauai	21.97	-159.71	(1950-99)	54.1
3	Kauai Coffee	Wahiawa	Kauai	21.9	-159.56	(1950-04)	89.7
4	Kauai Coffee	McBryde Station	Kauai	21.92	-159.54	---	--
5	Kauai Coffee	Bydswood Station	Kauai	21.93	-159.54	(1952-04)	150.4
6	East Kauai	Lihue Variety Station	Kauai	22.03	-159.39	(1964-99)	186.7
7	Waiahole	Kunia Substation	Oahu	21.39	-158.03	(1994-05)	52.8
8	Waimanalo	Waimanalo Experiment Station	Oahu	21.34	-157.71	(1970-00)	107.9
9	Molokai	Kualapuu Res.	Molokai	21.16	-157.04	---	--
10	Molokai	Kualapuu	Molokai	21.16	-157.04	(1950-77)	85.9
11	West Maui	Pohakea Bridge	Maui	20.82	-156.51	(1950-04)	49.3
12	West Maui	Field 906	Maui	20.83	-156.5	---	--
13	Up-country	Kula Branch	Maui	20.76	-156.33	(1979-05)	60.5
14	Waimea	Lalaumilo Field Office	Hawaii	20.01	-155.69	(1981-04)	42.9
15	Lower Hamakua	Hamakua Makai	Hawaii	20.05	-155.38	---	--
16	Lower Hamakua	Paauilo	Hawaii	20.04	-155.37	(1950-05)	241.1

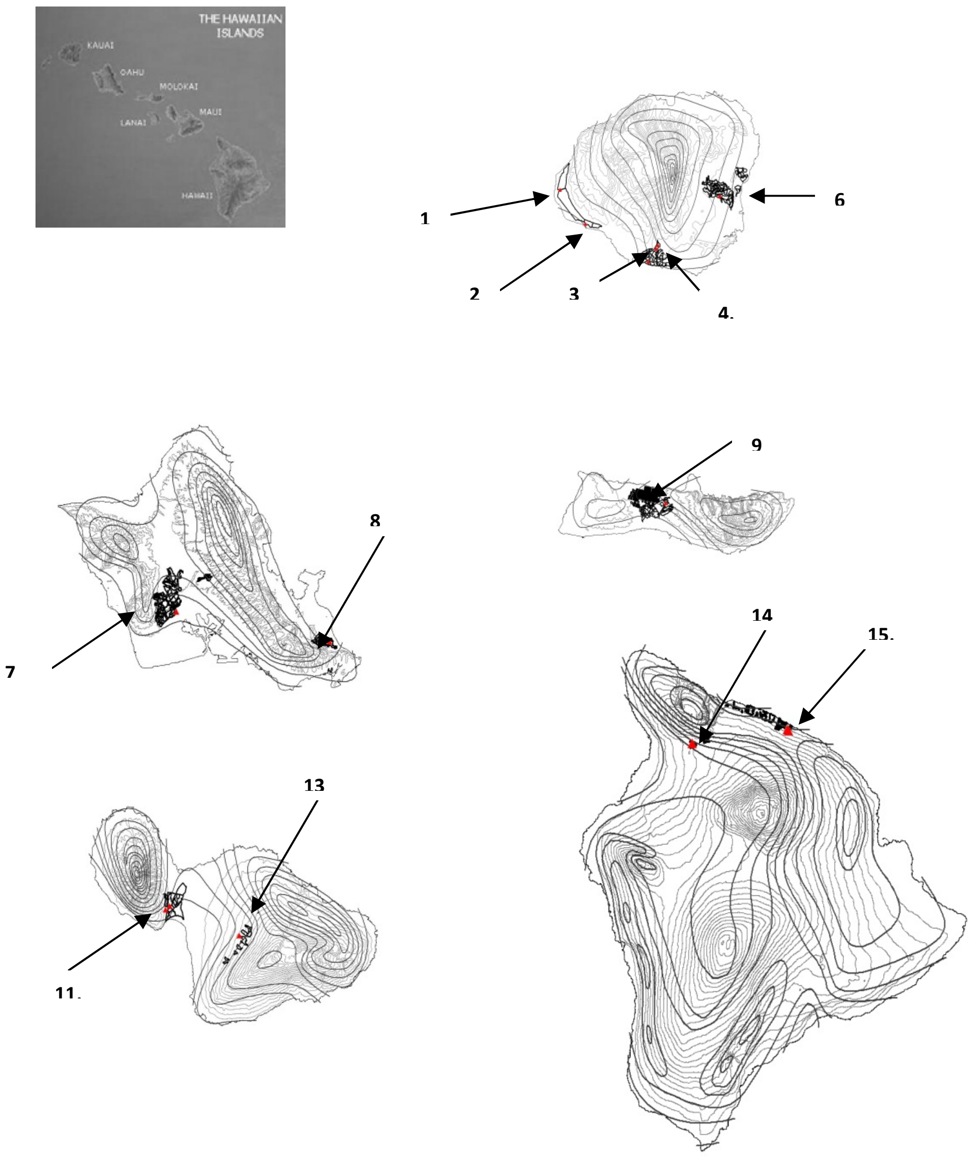

Figure 1. Selected 10 locations and climate data stations for the Hawaiian Islands. Stations are represented by the numbers their information is given in Table 3. Dark contours indicate isohyets gradients in rainfall and light contours indicate elevation. a) Kekaha and East Kauai in Kauai Island, b) Waiahole and Waimanalo in Oahu Island, c) Molokai in Molokai Island, d) West Maui and Kula in Maui Island, and e) Kamuela and Lower Hamakua in Hawaii (Big) Island.

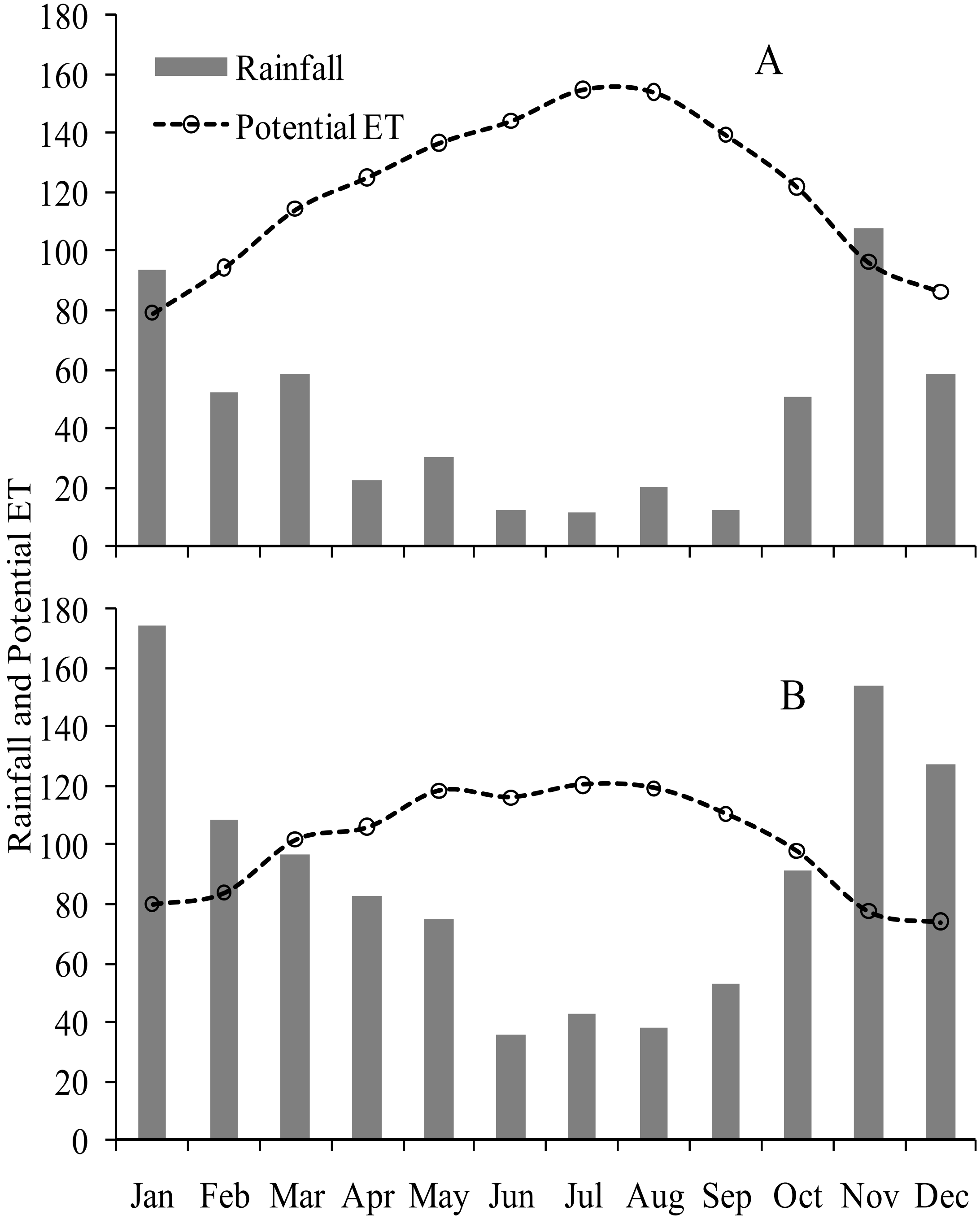

Figure 2. Intra-annual variability in rainfall (bars) and potential evapotranspiration (line) for a representative leeward (A, Waiahole) and windward (B, Waimanalo) locations.

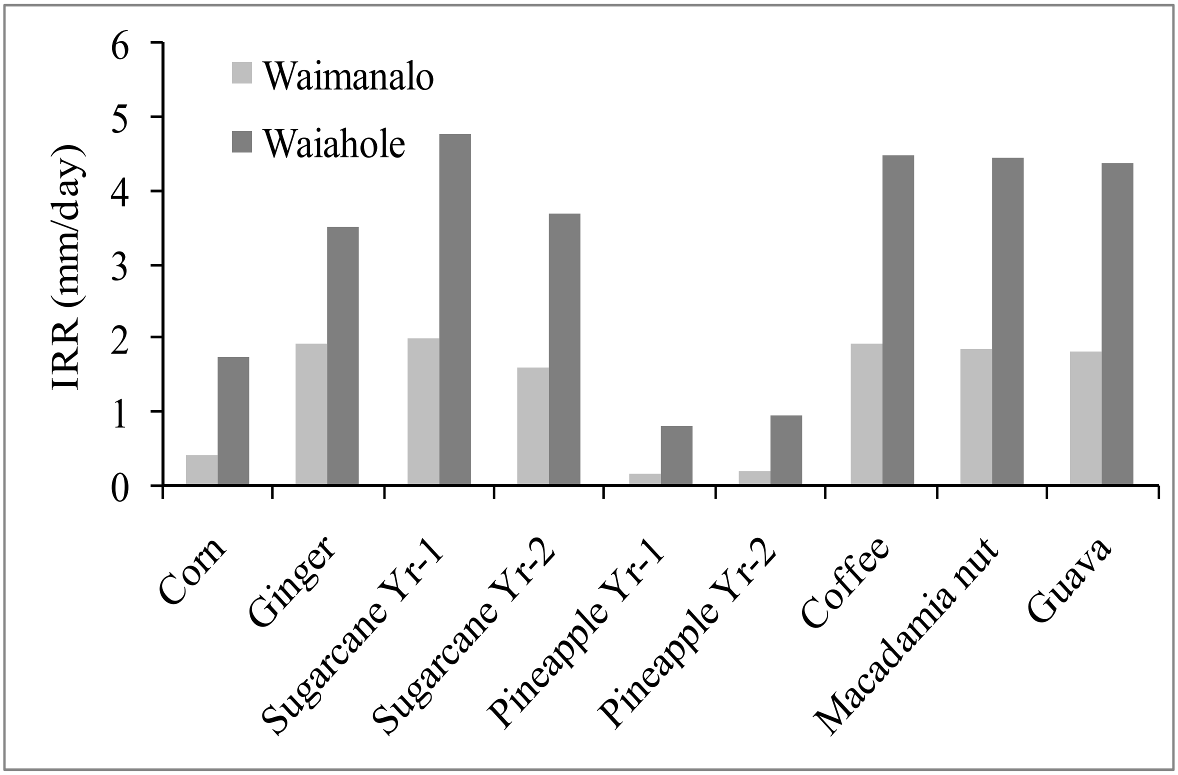

Figure 3: Comparisons of IRR calculated for Waimanalo and Waiahole locations for annual and perennial crops.

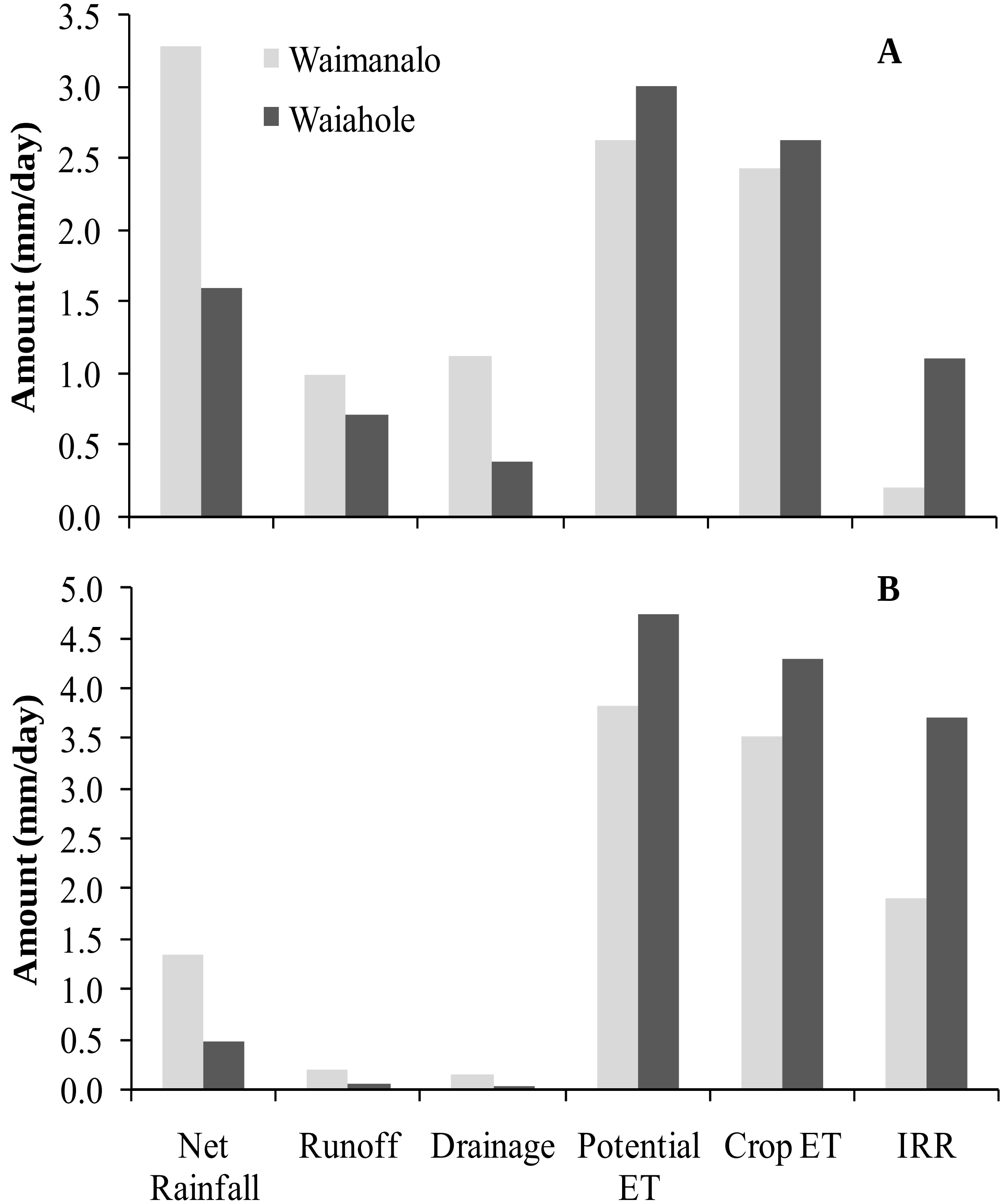

Figure 4: Water balance components and estimated IRR for Seed Corn using IMANSYS for Season-1 (A) and Season-2 (B) for Waimanalo and Waiahole locations.

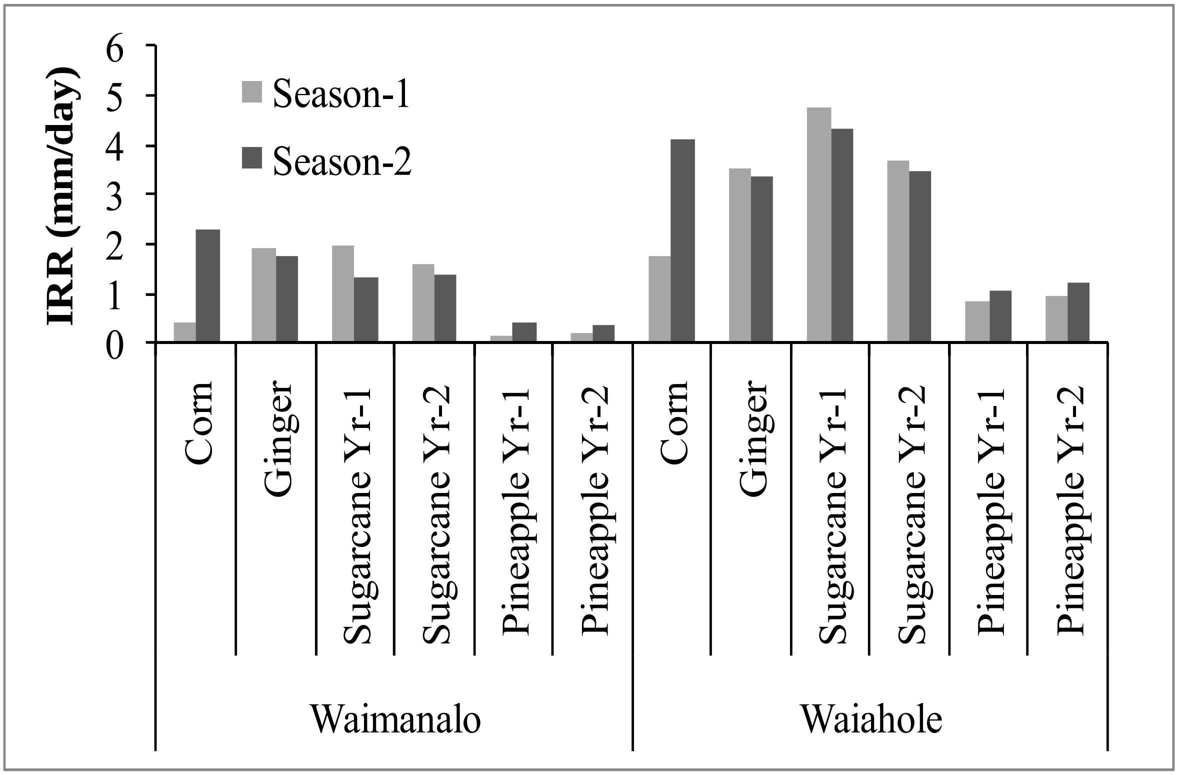

Figure 5: Variability in IRR between seasons at Waimanalo and Waiahole location on the Island of Oahu.

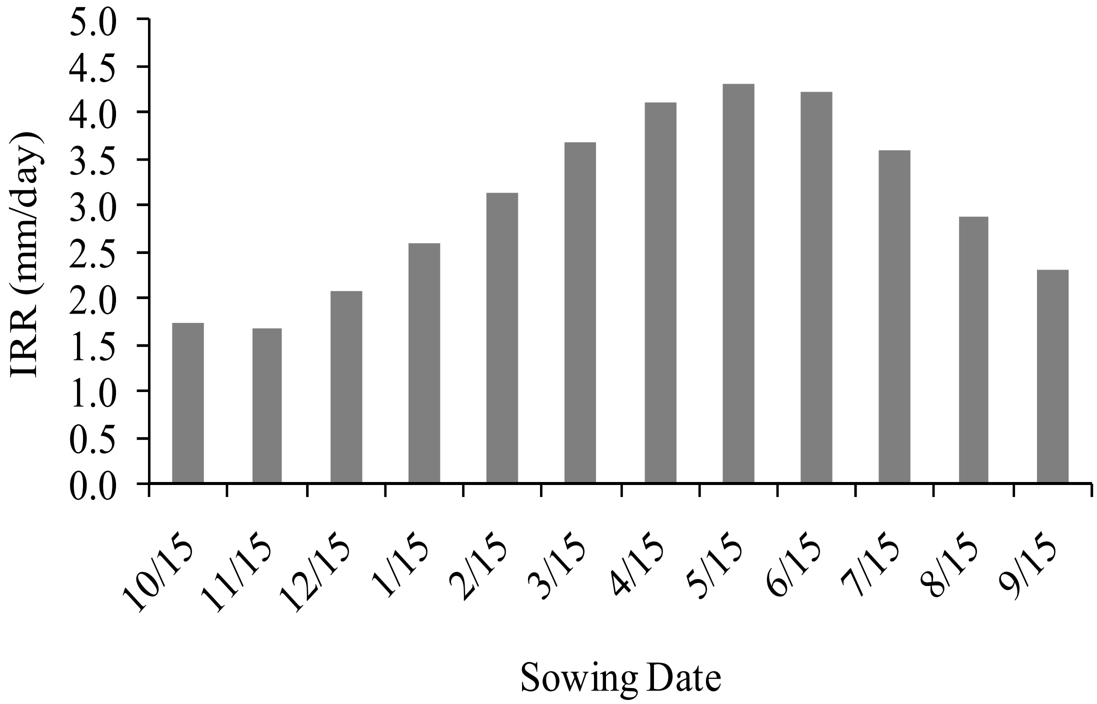

Figure 6: Variability in IRR with date of sowing for seed corn at Waiahole location on the Island of Oahu.

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